IGNEOUS ACTIVITY, METAMORPHISM, AND ORE-FORMATION IN WESTERN AUSTRALIA.

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CONTENTS.

1. INTRODUCTION.

The greater part of Western Australia is made up of Pre-Cambrian igneous rocks or rocks of metamorphic origin whose metamorphic characteristics have resulted in great part from igneous activity and associated earth movements. Moreover these rocks are both the home and source of the majority of our metallic mineral deposits. I feel therefore, in spite of the fact that the Pre-Cambrian geology of the State has been the subject of two previous Presidential Addresses to this Society (12, 39), that the volcanic history of the State has been the subject of one such address (59) and that one address has been given concerning metallogenetic epochs in Western Australia (87), that there is some justification for further consideration of the igneous record as seen in Western Australia and for an attempt to correlate this activity with metamorphism and ore formation. At the same time I feel that I owe an apology to one of our earliest Presidents, Mr. A. Gibb Maitland, if the title of my address is somewhat similar to that of his Presidential Address "The Volcanic History of Western Australia" (59), delivered to this Society some 18 years ago—in this period there has been some re-orientation of our views concerning Western Australian geology concomitant upon an increased knowledge of the distribution and relations of the rocks and of general petrogenetic principles and I should like to place before you this evening a summary, as I see it, of the present state of our knowledge concerning igneous activity and metamorphism in Western Australia

In dealing with such a wide area the work of many geologists must be taken into consideration—much of this work appears in published form in the various reports and bulletins issued from the Geological Survey Department but some is the result of research, both published and unpublished, by other workers—to all whose work I have utilised in compiling this summary, I express my thanks, but I should point out that the interpretation of the data used is mine and so I am solely responsible for any inaccuracies of interpretation.

Igneous activity implies the extrusion of molten rock materials (magmas) or their products at the Earth's surface (as in volcanic eruptions) or the intrusion of such magmas into the rocks of the outer crust of the Earth. Directly associated with igneous activity we have the production of metamorphic rocks (from pre-existing rocks affected by the hot intrusives and the earth-movements accompanying their emplacement) and ore deposits, which, in the case of primary deposits, are derived from rock magmas, generally during their final phases of consolidation. Such igneous activity was the dominant feature in this part of the world in Pre-Cambrian times, since when Western Australia has had a very quiescent history. Since Lower Cambrian times there is no evidence of igneous activity until the Tertiary, when volcanism on a very restricted scale is recognisable in the extreme northern and southern parts of the State. The absence of any signs of igneous activity during the immense period of time between the Lower Cambrian and Tertiary is, I think, one of the most remarkable features of Western Australian geology, especially when it is compared with the igneous record in Eastern Australia, and it emphasizes the extremely stable condition of the Western Australian shield throughout post-Cambrian times. There have undoubtedly been some oscillatory

movements of this continental block and slight folding and fracturing of the Palaeozoic and Mesozoic formations, but there is no evidence anywhere of violent diastrophisms or volcanism.

The events in the igneous history of Western Australia will now be considered, so far as possible in their chronological sequence.

II. THE PRE-CAMBRIAN SUCCESSION IN WESTERN AUSTRALIA.

Before proceeding to a consideration of the extensive igneous activity of Pre-Cambrian times it will be necessary to outline present views regarding the Pre-Cambrian succession. The latest opinions published regarding this matter are those of Forman (39) and Clarke (17 and 15) published in 1937, 1938 and 1931 respectively, and these are summarised in Table 1.

It will be seen that the successions as suggested by the two authors are in close agreement, the most outstanding difference being that Clarke has placed the Darling Gneiss Complex at the base of the succession, much against his will it seems, since he says (17, p. 21), "The writer inclines to the belief, based mainly on observations in the south of the Region [South-West Area of Western Australia], that the gneisses etc. of the Darling Complex are portions of the system next described [the Yilgarn-Kalgoorlie System] which have been extensively attacked and digested by acid intrusions. On the other hand Terrill considers (personal communication) that there is proof that the two systems are separated by an unconformity." The detailed succession for the Kalgoorlie District suggested by Forman (39, pp. xvii-xix) is indicated in Table 1, since this is the most completely investigated of the Pre-Cambrian areas of the State and further reference will be made to this section later.

Further work since the publication of Clarke's 1938 paper (17) necessitates some minor alterations to the succession and these are set down in the final column of Table 1. These amendments are:—

(a) The Stirling Range beds and Cardup Series, considered by both Clarke and Forman to be members of the Whitestone Series of Lower Archaeozoic age are transferred to the Proterozoic on the evidence yielded by further studies of these rocks (74, p. 51 and 19, p. 224). In connection with the position of the Stirling Range beds in the sequence it may be noted that Woolnough (102, p. 91) considers these beds to be intruded by granite but Clarke (personal communication) who has examined the area described by Woolnough has been unable to confirm the suggestion that the granite is intrusive into the Stirling Range beds and has found no evidence elsewhere in the Range that the granite is intrusive. The Stirling Range beds are therefore tentatively referred to the Nullagine period.

(b) The granitic rocks of late Archaeozoic age have been subdivided into two distinct groups:—(i) Older Granites belonging to an early period of granitization and granite intrusion under stress and (ii) Younger Granites of a later period of granite intrusion with which many of the State's metalliferous deposits appear to be genetically related. The evidence for this subdivision has been previously set down by the author (77). The granitic components of the migmatitic gneisses of the Darling Complex are included with the Older Granites rather than at the base of the succession as suggested by Clarke.

TABLE I.

THE PRE-CAMBRIAN SUCCESSION IN WESTERN AUSTRALIA.

AGE.	FORMAN (1937).		CLARKE (1938).	PRIDER (1945).
	W.A. Generally.	Kalgoorlie District.		
LATE PROTEROZOIC or LOWER CAMBRIAN.	Basic dykes (epidiorite, dolerite, norite)	Dolerite and Gabbro	Basic dykes (epidiorite, dolerite, norite)—Probably feeders of Nullagine volcanics	Basic dykes (epidiorite, dolerite, norite)—Period of base metal ore formation.
PROTEROZOIC.	*Igneous contact* — — — Nullagine Series	Kurrawang Series	Nullagine Series	Nullagine Series (including Stirling Range beds and Cardup Series).
ARCHAEOZOIC.	*Unconformity* .... Gneisses, granite and porphyry	Granite and porphyry	Later Granite invasion (major period of ore formation)	Younger Granite (period of auriferous ore formation and economically important pegmatites)
			Igneous	*contact* — — — — Older Granite (gneisses and migmatites)—Period of granitization.
	Igneous contact — — —	Younger Greenstones	Basic dykes [? Younger Greenstones]	Younger Greenstone Phase (period of auriferous ore formation)
	Igneous	*contact* — — — — Kundana Series		
	Unconformity	.... White Flag—Yindarlgoorda Series	Yilgarn-Kalgoorlie System: Whitestone phase, including Stirling Range beds	Yilgarn-Kalgoorlie System: Whitestone phase
	Whitestone Series (= Mosquito Creek Series = Jimperding and Cardup Series)			
	Unconformity	.... Black Flag—Tuffaceous Series		
	Greenstone Series (= Warrawoona Series)	Kalgoorlie Series (= Older Greenstones)	Older Greenstone phase	Older Greenstone phase
			Unconformity .... Darling gneiss complex	

Subdivision at Kalgoorlie as given by Forman, except that "White Flag-Yindarlgoorda Series" is replaced by "Yindarlgoorda Series" and "Black Flag-Tuffaceous Series" by "Black Flag Series."

(c) It is suggested that the Younger Greenstone period was a period of ore formation. The reasons for this addition are developed in a later section of this paper.

(d) Forman's "Black Flag—Tuffaceous Series" and "White Flag—Yindarlgoorda Series" of the Kalgoorlie District are replaced by "Black Flag Series" and "Yindarlgoorda Series" respectively.

III. ARCHAEOZOIC IGNEOUS ACTIVITY.

A. OF YILGARN-KALGOORLIE TIMES.

The rocks of the Yilgarn-Kalgoorlie System, the basal System in Western Australia, forming as they do the country of the more important auriferous deposits, have been more closely studied than those of later formations. Moreover some of these localities, because of their relatively greater economic importance, have been more intensively studied than others. These studies were begun in various widely spaced localities and different investigators have given different names to what are probably more or less contemporaneous formations. Much of this ambiguity has however been overcome by the recent work of Clarke (17 and 15) and Forman (39) which has been directed towards the correlation of these formations in the different parts of the State. In this present paper all the pre-granite formations are considered to belong to the Yilgarn-Kalgoorlie System and the igneous activity of these times will be considered from the record as seen first of all in the various natural regions (14) in the southern half of the State and then as developed in the northern half of the State.

1. SOUTH-WESTERN AUSTRALIA.

This region extends as far north as latitude 26° S. Within this part of the State are situated the more important gold-bearing areas (where there is an extensive development of the greenstone phase of the Yilgarn-Kalgoorlie System) and the important agricultural areas (where there is, so far as known at present, a predominance of granitic and gneissic rocks and the greenstone phase can only be detected in remnant structures).

(a) *Kalgoorlie and Murchison Natural Regions.*

Throughout the various mining fields which have been examined of later years, the oldest recognisable rocks are of volcanic origin and are generally referred to as the *Older Greenstone Series.* They are all metamorphosed to some extent and in many areas regional metasomatism, on which there is impressed a more intense local metasomatism in the vicinity of ore-bodies, has tended to reduce all varieties to a common end product. Nevertheless from their relict structures they can be seen to be largely basaltic lava flows (very often pillow lavas) with associated fragmental volcanic rocks. Of recent years the pillow structure of these basaltic rocks has been utilised in determining the stratigraphical order in the highly folded greenstones. Although pillow structure had been recognised much earlier (Honman for example in 1917 described pillow lavas from the Yerilla District (46, p. 26)) it was not until the American geologists of the Western Mining Corporation in about 1932 "rediscovered" these structures, that their use for unravelling structure was realised in Western Australia.

The least altered of these basic lavas are fine-grained amphibolites in which the pyroxenes of the original basalts have been replaced by pale green fibrous amphibole. With further metasomatism (propylitisation) the fine-grained amphibolites give way to fine-grained greenstones in which the amphibole is replaced by chlorite and progressive carbonate metasomatism is noticeable in the replacement of all rock minerals by various carbonates yielding rocks generally referred to as "calc schists." The fine grained amphibolites, in areas which have suffered high grade metamorphism, are represented by hornblende schists (schistose plagioclase amphibolites) in which the original basaltic textures are completely obscured by recrystallisation. The origin of such rocks however is often clearly indicated by the presence of pillow structure which is retained even in completely recrystallised rocks.

The most closely studied area of the Older Greenstone Series is in the vicinity of Kalgoorlie and the petrography of the fine-grained amphibolites, greenstones and calc schists of this area has been fully dealt with by Simpson and Gibson (89, pp. 16-21), Thomson (97, pp. 631-5), Feldtmann (29, pp. 17-23) and Stillwell (91, pp. 20-1).

In some areas a minor development of rhyolitic flows occurs interbedded with these basaltic lavas, thus in the Yerilla District of the North Coolgardie Goldfield, Honman (46, p. 25) describes a rhyolitic series which is contemporaneous with the basic lavas and occurs interbedded with them. The volcanic series developed at Yerilla consists predominantly of greenstones such as fine-grained amphibolites (very similar to those of Kalgoorlie) and amphibolite schists. Many of these greenstones have their volcanic characteristics—vesicular, amygdaloidal and pillow structures well preserved. Periods of explosive volcanism are represented by the agglomerates interbedded with the greenstones. Acid lavas are represented by a minor development of rhyolites also interbedded with the greenstones.

Mention of rhyolitic rocks occurring associated with fine-grained greenstones in many other mining districts is to be found in various publications from the Geological Survey of Western Australia but owing to the possibility that they are members of later series, such as the Black Flag and Yindarlgoorda volcanic series of the Kalgoorlie District (39, p. xix) these will not be considered here. The Yerilla rhyolites however appear to belong definitely to the Older Greenstones and indicate that acid lavas were extruded in the earliest part of the Archaeozoic Era.

In the goldmining areas situated west from Kalgoorlie the lavas of the Older Greenstone Series are represented by schistose amphibolites, the significance of which will be discussed later in dealing with the metamorphism of these rocks. In spite of the extensive recrystallisation of these rocks they still retain the characteristic pillow structure of the Older Greenstones. This pillow structure is very evident in the fine-grained amphibolites of Coolgardie and in the completely recrystallised schistose amphibolites in the vicinity of Southern Cross (27, p. 75. see also fig. 1) in which amygdaloidal structures are also retained. Ellis (27, p. 75) considers that fragmental volcanics (volcanic breccias and tuffs) are interbedded with the lavas of the Older Greenstone Series of Southern Cross. In the southern Yilgarn no acid lavas have been recognised but rhyolite-porphyries are present in the northern Yilgarn near Marda (4, p. 154) and are considered to be part of the volcanic Greenstone Series.

In most of the mining areas of the Central Goldfields the basaltic lavas of the Older Greenstones Series contain intercalated bands of sediments (generally jaspilites).

The Older Greenstone Series then, which is placed at the base of the geological succession in Western Australia, is a series of basaltic flows of spilitic character with associated basic agglomerates and tuffs and a minor development of sedimentary jaspilites and acid volcanics such as rhyolites and their associated tuffs and breccias. In view of the spilitic character and common occurrence of pillow structure, these lavas were probably largely submarine extrusions.

The later part of the Yilgarn-Kalgoorlie Period is characterised by various epochs of volcanicity. According to Forman (39, p. xix) there are several series intermediate in age between the Older and Younger Greenstones and these have been examined in detail in the country to the west, north and north-east of Kalgoorlie (92, 93). The *Black Flag Series* lies on top of the Older Greenstones and is composed of rhyolite—and probably trachyte-tuffs, tuff-agglomerates and tuff-breccias with occasional thin bands of lava and flow breccias and erosion sediments such as grits, quartzites and mudstones—the record then is one of explosive volcanism associated with acid extrusions. The rhyolitic phase of the upper part of the Older Greenstones that has been mentioned earlier may perhaps be related to the Black Flag Series since no information is available regarding the relationship, conformable or otherwise between the Black Flag and Older Greenstone Series, except that the Black Flag Series is higher in the succession.

Forman (39, p. xix) refers to this series as the Black Flag-Tuffaceous Series, since Feldtmann in an unpublished report (32) referred to these rocks as the Tuffaceous Series. In view of the fact that Feldtmann's report remains unpublished and that the name Black Flag Series was used by Gustafson and Miller (41, p. 293) for this group of rocks in work published early in 1937 prior to Forman's publication (39) of the hyphenated name, it is best to use the name which has priority, viz. Black Flag Series.

The Black Flag Series is overlain unconformably by the Yindarlgoorda Series. Forman (39, p. xix) refers to this series as the White Flag-Yindarlgoorda Series since he considers the White Flag Series as established by Talbot (described in an unpublished report (92)), to be the equivalent of the Yindarlgoorda Series of Bulong, described by Feldtmann as pebble breccias (30, p. 20). In the text of his publication Feldtmann does not mention the name Yindarlgoorda Series, but this name does appear on his published map (30, plate 1) and so can be regarded as published, and therefore having priority the name Yindarlgoorda Series should replace "White Flag Series" or "White Flag-Yindarlgoorda Series." The Yindarlgoorda Series consists of andesitic and dacitic lavas and associated agglomerates and tuffs with interbedded erosion sediments. The petrography of the volcanic members has been described by Fletcher in Talbot's report (92).

The only remaining series—the Kundana Series, lying unconformably on the Yindarlgoorda Series is one of erosion sediments without any evidence of igneous activity. The widespread volcanism of the early

Archaeozoic appears then to have died out after the extensive eruptions which yielded the Yindarlgoorda volcanics and there is no further record of igneous activity until the intrusion of the Younger Greenstone Series now to be described.

The Younger Greenstone Series represents a hypabyssal phase of basic magma intrusion which appears to be the final stage of the igneous activity of Yilgarn-Kalgoorlie times. Rocks of this group, intrusive into all the pre-existing formations are represented in most of the mining fields in the belt of country extending from Norseman through Kalgoorlie to Leonora and Laverton and thence to Wiluna and Forman (39, p. xxv) considers the Younger Greenstones to be developed in the Southern Cross District and in this assertion is supported by Ellis (27, p. 84). However the Younger Greenstones appear to be of minor development in the Yilgarn Goldfield. Their distinctive characteristics may have been largely obscured by metamorphism, which in this area is of higher grade than in the regions mentioned above, so that they can only be distinguished from the recrystallised older basalts with difficulty. The Younger Greenstone Series is not nearly so important economically as in the more eastern areas where, especially at Kalgoorlie, they form the country of nearly all the more important auriferous lodes.

The Younger Greenstone magma appears to have been extensively differentiated prior to intrusion and is represented by earlier ultrabasic intrusions, followed by a basic (doleritic phase) and later by an intermediate to acid phase. Members of each of these three main groups are developed in most of the mining centres in the belt of country mentioned but have been most closely studied at Kalgoorlie. As with the Older Greenstones there has been considerable alteration of the rocks by post-crystallisation earth movements together with regional and local metasomatism but in spite of such alteration the three main phases—ultrabasic. basic and acid can be recognised. At Kalgoorlie they are represented by:—

(i) Ultrabasic phase:—

(a) Serpentines and various metasomatised types such as talc-mesitite rocks and fuchsite-carbonate-quartz rocks considered to be derived from peridotites (29, p. 14 and pp. 35-8).

(b) Hornblendites and metasomatised types such as talc-chlorite-carbonate rocks and some fuchsite-carbonate-quartz rocks derived from pyroxenites (29, p. 14 and pp. 32-4).

(ii) Basic phase:—

Various low grade metamorphic products of dolerite and quartz dolerite. The least altered types are uralitised dolerites and uralitic quartz dolerites (91, p. 21) termed "amphibolites" and "epidiorites" by Feldtmann (29, p. 14) and "amphibolites" by Thomson (97). With increasing propylitization (chloritization, albitization and carbonatization) the original quartz dolerites are represented by various quartz dolerite greenstones and their highly carbonatized equivalents, the bleached quartz dolerite greenstones (97, pp. 646-54; 91, pp. 25-8; 29, pp. 27-9).

(iii) Intermediate to acid phase:—

Is represented by (i) chloritized hornblende porphyrites (91, p. 36) and a more acid group (ii) albite porphyries or keratophyres (97, p. 658; 91, p. 31) which are termed albite porphyrites by Feldtmann (29, p. 39).

Petrographic details regarding these rocks are given in the various references cited.

Thomson (97, p. 663) considers that the peridotites were the earliest intrusives, followed closely by the pyroxenites and, after an interval, by the quartz dolerite and its local variants. It is generally agreed that the hornblende porphyrites and albite porphyries occur as later dyke-intrusions. The hornblende porphyrites are, in my opinion, earlier than the albite prophyries (72). All of these rocks are considered by Thomson (97, p. 662), Feldtmann (29, p. 87), Stillwell (91, p. 60) and Prider (72) to be co-magmatic and to represent a magmatically differentiated series which has suffered low grade metamorphism and subsequent metasomatism. Gustafson and Miller (41, p. 314) on the other hand consider that the albite porphyries (and ore solutions) probably came from "the underlying granite batholith." When all the factors of occurrence, petrology and type of associated mineralisation (mentioned in a later section) are considered it appears most probable that the albite porphyries are genetically related to the greenstone rather than the later granite magmas.

The Younger Greenstone period was therefore a period of hypabyssal igneous activity of a basic magma. The earlier ultrabasic and basic phases appear to be largely sills or laccoliths (as at Kalgoorlie (41, p. 296) and Wiluna (5, p. 3)) whereas the later acid porphyry phase is represented by dyke intrusions.

(b) *Jarrah, Stirling and Wheat Belt Regions.*

Here the record of Yilgarn-Kalgoorlie igneous activity is very fragmentary, being represented only by xenolithic bands or lenses within a wide expanse of granitic gneisses or by thin layers interleaved with the meta-sediments which appear to be the Whitestone phase of the Yilgarn-Kalgoorlie system. This south-western corner of the State is made up essentially of Archaeozoic rocks which are dominantly gneissic and granitic in character, with a minor development of an older metasedimentary series which is considered to be the Whitestone phase of the Yilgarn-Kalgoorlie System. It must be noted however, that these para-schists are probably of greater extent than the known outcrops suggest, since much of the country is covered by weathering products. Professor Clarke informs me for example that there is a band of schists 30 miles wide between Pt. Ann and Hopetoun on the south coast. These whitestones have been intruded by later gneissic granites which contain numerous basic lenses and also remnants of the whitestones themselves.

Both the extensive areas of whitestones and greenstone xenoliths in the gneisses are pre-gneiss (76) and Forman (39, p. xxvi) considers it probable that the greenstones of Bolgart are lower in the succession than the whitestones of the Jimperding Series. The greenstones have only been studied in detail in a few areas. At Toodyay (76, p. 119) they occur as basic bands and lenses of various amphibolites which are considered to be the result of recrystallisation of earlier basic igneous rocks the

original structures of which have been completely obscured by recrystallisation. Lenses of hypersthenite and associated cordierite-anthophyllite rocks occur in the gneiss at Toodyay (73) and also small areas of banded quartz-magnetite-grunerite (and hypersthene) rocks (=metajaspilites). The whole assemblage of xenoliths in the gneiss may well be imagined to be highly metamorphosed derivatives of the older Greenstone Series which, in many places, contains interbedded jaspilites—the amphibolites being derived either from basaltic lavas or doleritic rocks, the hypersthenites representing the earlier ultrabasic phase of the Younger Greenstones. At Dangin (78) lenses of amphibolite and hypersthenite, identical in character with some Indian charnockites, are present and may be correlated with the Toodyay greenstones and therefore with the Kalgoorlie greenstones. These basic lenses are a characteristic feature of the gneisses of the south coast both to the east and west of Albany and of the gneisses of the south-west coast between Capes Leeuwin and Naturaliste. Carroll (10, p. 169) considers these basic lenses to be derived from tuffs. They have, however, been so thoroughly recrystallised that all original structures have been lost and I consider that the most that can be said of them with certainty is that they were derived from basic igneous rocks, but whether these were pyroclastics, lavas or hypabyssals is not determinable.

Evidence of igneous activity in the Whitestone phase of the Yilgarn-Kalgoorlie System of the South-West is to be seen in the Toodyay district in the form of schistose plagioclase amphibolites interleaved with the metamorphosed erosion sediments—these amphibolites (76, p. 104) may have been either flows or sills which have suffered the same high grade (sillimanite zone) metamorphism as the associated para-schists.

(c) *Warburton Natural Region.*

The main Pre-Cambrian rocks here are those of the Warburton Range area, the westernmost exposures of a Pre-Cambrian belt which extends in an easterly direction to the Musgrave and Everard Ranges in South Australia. There is too much doubt regarding the succession in this area to warrant any detailed consideration here. Talbot and Clarke have described an older series of greenstones comparable with the greenstones of the Central Goldfields (94, p. 118) but Forman (38) considered these greenstones to be representatives of the Nullagine System and in this was supported by petrological observations of R. W. Fletcher (35). Forman (39, p. xxiv) now considers that some of the greenstones which he formerly thought to be of Nullagine age should be referred to the older Pre-Cambrian. The occurrence at Mt. Aloysius in the eastern part of the Warburton area of charnockitic rocks (94, p. 129) makes it probable that the gneissic belt to the north of the Warburton Range is similar to the gneissic areas of the Wheat Belt of the South-West—the charnockitic rocks being similar to those from Dangin (78) which, earlier in this paper, have been regarded as remnants of the Yilgarn-Kalgoorlie System which have escaped complete assimilation during the Older Granite period. Whatever be the age of the Warburton Range greenstones there is evidence, in these charnockitic rocks, of very early Archaeozoic activity of a basic magma.

2. THE NORTH-WEST NATURAL REGION.

In this region there are two main series of rocks which are earlier than the granites and gneisses and therefore comparable in age to the Yilgarn-Kalgoorlie System. These are the Warrawoona Series (dominantly of greenstones) and the Mosquito Creek Series (of metasediments) and they are regarded by Forman (39) as contemporaneous with the Greenstone and Whitestone Series respectively.

Evidence of igneous activity of Yilgarn-Kalgoorlie times in the Pilbara is confined to the Warrawoona Series which is made up mainly of igneous rocks with a minor development of normal erosion sediments. With the recently published reports of the Aerial, Geological and Geophysical Survey of Northern Australia there has been an increase in our knowledge of the distribution and structure of these rocks but there is still very little information about their petrography.

The igneous rocks of the Warrawoona Series are similar in many respects to those of the Kalgoorlie (Older Greenstone) Series, consisting largely of fine-grained greenstones (basaltic lava flows) and acid volcanics such as felsites together with various acid and basic flow-breccias. In the sheared zones in which most of the mining centres are located, these volcanics are represented by various schists—chlorite-carbonate schists for example are regarded as the sheared and metasomatised equivalent of the fine-grained greenstones (basaltic lavas and tuffs (33, p. 3)). The acid phase seems to be more widely developed than in the Older Greenstones of the Central Goldfields areas where, as has been previously noted, acid volcanic rocks are, in a few places, interbedded with the greenstones. None of the workers in this region have attempted to draw up a typical section of the Warrawoona Series so that, from the literature and published maps it is difficult to learn anything regarding the order of extrusion of the different volcanic rocks. The early Archaeozoic in this region was however a period of extensive volcanism, as it was in the southern part of the State.

3. THE NORTH KIMBERLEY NATURAL REGION.

The Archaeozoic rocks of this region are even less known than those of the Pilbara and they have only been cursorily examined at a few mining centres. The pre-granite rocks of this region are made up of a variety of metasediments and basic lavas (including pillow lavas) with interbedded tuffs and rare quartz porphyries which may be either sills or flows. Finucane (in A.G.G.S.N.A. Western Australian Reports 27 and 29) states that these rocks are members of the Mosquito Creek Series but Forman (39, p. xxii) considers that in the vicinity of Hall's Creek in the East Kimberley Division the oldest rocks exposed are greenstones (basic lavas and tuffs) comparable to the Warrawoona Series of the Pilbara, which are overlain conformably by sediments comparable to the Mosquito Creek Series.

Too little is known of the distribution, structure and petrography of these rocks to warrant any further consideration of them here.

Conclusions.

It is evident from the foregoing that throughout the State the early Archaeozoic was a period of intense volcanism. The oldest recognisable rocks are of basaltic character, probably largely submarine flows characterised by pillow structure and interbedded with pyroclastics and cherty sediments. These basalts appear to be very uniform in character but during the later stages of this period of activity some acidic lavas were extruded. The succeeding periods of Yilgarn-Kalgoorlie igneous activity (Black Flag and Yindarlgoorda Series) were of extrusive type but of entirely different character being dominantly acid (rhyolitic and dacitic) lavas with a more extensive development of flow-breccias and pyroclastics, and being probably largely subaerial deposits as compared with the submarine extrusions of the earlier Archaeozoic. The final phase of Yilgarn-Kalgoorlie igneous activity was in the form of hypabyssal doleritic intrusions (the Younger Greenstone Series) characterised by considerable diversity in rock types due to magmatic differentiation All of these rocks have been altered to some extent, either metasomatically or by regional metamorphism consequent upon the widespread activity of granitic magma, the nature of which will now be discussed.

B. THE OLDER GRANITE PERIOD.

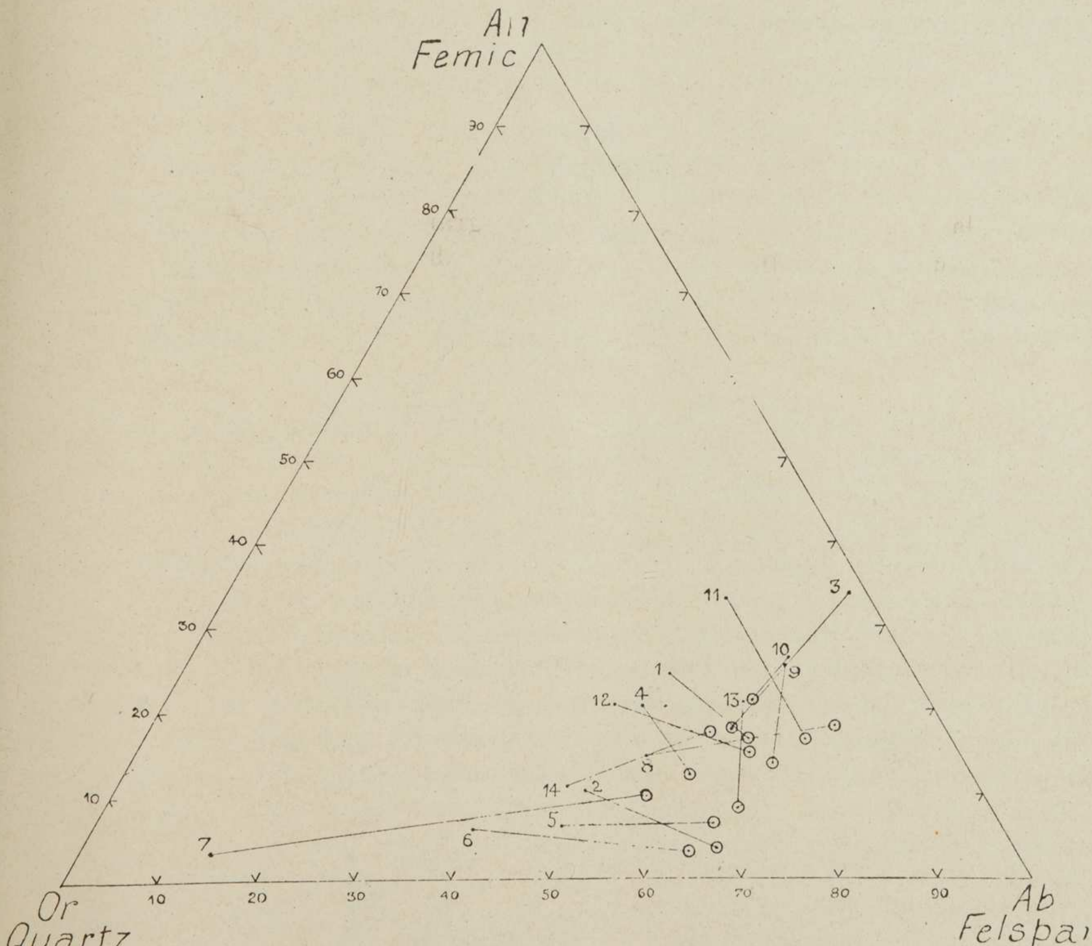
A glance at the latest (1933) geological map of Western Australia (40) will show that the greater part of the southern half of the State (south of latitude 26° S.) is made up of granitic rocks (granites and gneisses), enclosing comparatively narrow north-west trending strips of Yilgarn-Kalgoorlie rocks, and most Western Australian geologists are agreed that the granitic rocks are intrusive into the greenstones and associated sediments of the Yilgarn-Kalgoorlie System. Clarke (16, p. xl) has dealt with our changing conceptions of the nature of this "granitic" area of approximately 300,000 square miles, the present conception being that this area consists largely of a folded complex of Archaeozoic metamorphic rocks which have been extensively granitized to yield various gneisses and later intruded by granite stocks.

Of recent years evidence has accumulated which indicates that there are at least two distinct periods of granite emplacement (74, p. 29; 77; 27, p. 91; 76, p. 129). The earliest period, here referred to as the Older Granite, is now represented by granitic gneiss, probably the most extensive formation developed in South Western Australia, the later period (Younger Granite) being one of dyke and stock intrusions.

The gneisses of the Older Granite phase are largely of migmatitic nature showing considerable local variation in character due to assimilation of the older rocks whose original presence is indicated by the incompletely absorbed xenoliths. As mentioned previously these xenoliths may be correlated with rocks of the Yilgarn-Kalgoorlie System, from which they differ mainly in texture due to extensive recrystallisation during the period of migmatisation. These gneisses have been studied in detail in comparatively few localities. The Toodyay District is the best area yet studied for illustrating their relationships to the older rocks. Here they vary locally from potassic microcline granite gneisses to sodic oligoclase granite gneisses, and occur as large sill-like masses (one of which is estimated to be 5,400 feet thick) conformable with the associated meta-

sediments (76, p. 85). These gneisses contain numerous xenoliths of both metasedimentary and meta-igneous rocks (generally coarse hornblende granulites derived from older basic igneous rocks) and are similar in this respect to the gneissic complex wherever it has been studied. In the vicinity of such basic enclosures the granitic gneiss is often hybridised (76, p. 122) yielding more basic hornblende-bearing gneisses. In places where hypersthenites have been granitized the resultant rocks are cordierite-hypersthene-quartz-felspar gneisses, which would, except for the very clear demonstration of their origin as seen at Dangin (78), be normally regarded as metasedimentary rocks. These hypersthenites and related rocks are of charnockitic nature (78) closely resembling the charnockitic suite of India (44) and are fairly common in the gneissic complex (as for example at Northampton, Albany, Toodyay, Dangin, Fraser's Range and the country to the north-east of the Warburton Range).

The banding of the hybridised gneisses generally conforms to the bedding of the invaded metamorphic rocks. In the Toodyay gneisses this banding is due to a parallelism of xenoliths and to a parallel flow orientation of the microcline phenocrysts and the augen developed by protoclasis

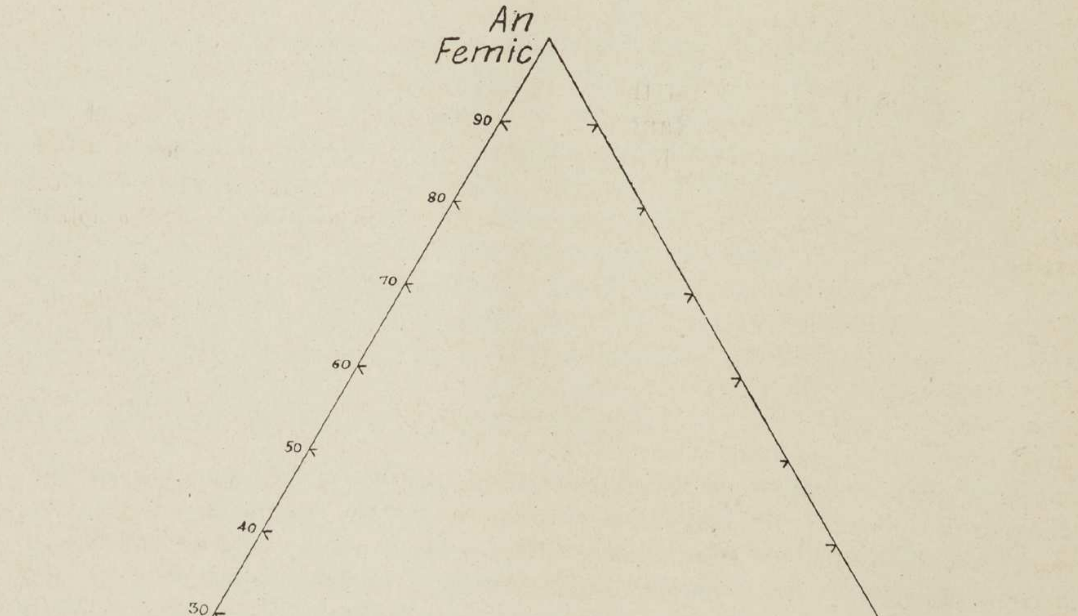


Text Fig. 1.—**Older Granites**—Larsen triangular diagrams (50) of rocks which appear to belong to the Older Granite period. Circles are quartz-felspar-femic ratios, dots are or-ab-an ratios. 1, Oligoclase granite gneiss, Toodyay (76, p. 110); 2, Microcline granite gneiss, Toodyay (76, p. 110); 3, Hornblende granite gneiss, Toodyay (76, p. 123); 4, Hybrid gneiss, Armadale (74, p. 36); 5, Granite gneiss, Russell Range (84); 6, Granite gneiss, Pine Hill, Russell Range (84); 7, Cordierite-hypersthene-quartz-felspar gneiss, Dangin (78). Nos. 8-14 are all recorded as "granodiorite" in the records of the W.A. Government Chemical Laboratory and the Geological Survey of W.A. I have not examined this group of rocks and there is some doubt as to whether they should be included with the Older or with the Younger Granites. They are from the following localities:—8, Mosquito Creek (83, p. 20); 9, Kookynie (83, p. 20); 10, Cue (83, p. 20); 11, Bowgada (84); 12, Jitarning (84); 13, Morawa (84); 14, Jibberding (84).

of these phenocrysts. From an examination of the fabric of these gneisses and the associated quartzites (76, p. 109) it appears that the emplacement of the Older Granite coincided with the orogenic period responsible for the metamorphism of the Yilgarn-Kalgoorlie System—the main period of constructive metamorphism in Western Australia.

The gneisses of the areas that have been mentioned (Toodyay and Dangin) are similar in all respects to those of most other parts of the Western Australian Pre-Cambrian complex. In view of their similarity of structure and relations to the older rocks there can be little doubt that they were all more or less of contemporaneous formation, as are the granitic gneisses of the North-West and North Kimberley Natural regions.

Much of the granitic gneiss appears to be orthogneiss but replacement gneisses and migmatitic gneisses resulting from the metasomatism and injection of the Yilgarn-Kalgoorlie System also cover extensive areas. The Older Granite period was, therefore, one of State-wide activity of a very mobile granitic fluid and granitization was a characteristic feature of the igneous activity of this period. The chemical characteristics of the Older Granites are illustrated in Text Fig. 1.



Text Fig. 2.—**Younger Granites**—Larsen triangular diagrams (50) of granites which appear to belong to the Younger Granites. Circles are quartz-felspar-femic ratios, dots are or-ab-an ratios. 1, Kookynie (84); 2, Southern Cross (83, p. 16); 3, Mulgine (84); 4, On No. 1 Rabbit Proof Fence at 69 miles north of Burracoppin (84); 5, Mt. Ridley (84); 6, Mahogany Creek (83, p. 18); 7, Boya (84); 8, Canning Dam (77, p. 144); 9, Gosnells (22, p. 254); 10, Mundaring (84); 11, Bannister (83, p. 18); 12, Norseman (83, p. 18); 13, Ravensthorpe (83, p. 20); 14, Fraser's Range (84); 15, Coolgardie (83, p. 16); 16, Beeragoona (84); 17, Buldania Rocks (84).

C. YOUNGER GRANITE.

The latest phase in the development of the granite and gneiss complex was the intrusion of massive granites in the form of stocks and dykes, accompanied by pegmatites, aplites and quartz veins. These granites transgress the gneissic structure of the Older Granites and the bedding and schistosity of the Yilgarn-Kalgoorlie rocks. They often enclose xenoliths of the older gneisses and in some instances (as in the Darling Range near Perth) there is such an intimate mixture of the older and younger granite phases that it is impossible to map them separately.

The Younger Granite in the Darling Range is characterised by its potassic character, microperthitic microcline being constantly present, but in other areas they are more sodic trondjhemitic types. The chemical composition of such granites which, from the available data, can reasonably be regarded as belonging to the Younger Granite series is graphically represented in Text Fig. 2.

The Younger Granite is accompanied by end phase quartz-felspar- and granite-porphyries, aplites, pegmatites and quartz veins. Many of these dykes and veins are economically important by virtue of their content of such minerals as gold, mica, felspar, cassiterite, tantalite and so on.

No detailed systematic examination of the Western Australian granites has yet been attempted and it is probable that there are a number of igneous epochs represented in this Younger Granite phase. Study of some granites from the Darling Range (77) indicates that some at least of the massive granites which are absolutely devoid of any visible directed structure and are the most normal looking of the Western Australian granites are of palingenetic origin, resulting from the rheomorphism of the Older Granites.

Much work remains to be done in connection with the origin and correlation of the Western Australian granitic rocks. In spite of the fact that they are the most ubiquitous rocks in the southern half of the State and that the emplacement of the granite masses was probably one of the most important geological events in Western Australia, since it was the major factor in the widespread metamorphism of the Archaeozoic formations and in the formation of many important ore deposits, the granitic rocks have not been closely studied. This is due in part to the fact that in inland Western Australia rock outcrops are generally poor, being largely obscured by weathering products, but also in part because it is not regarded as an economically important matter since the granitic rocks do not generally carry important auriferous deposits. However the possibility of the areas of granitized greenstones being potential auriferous country has been mentioned by Ellis (27, p. 14) and the occurrence of auriferous veins in the granitized gneisses of Westonia (61, p. 19), in the granite at Yarri (54, p. 6) and in the granite at Kundip near Ravensthorpe (personal observation) and doubtless in other places, in addition to the fact that the Younger Granites are the source of many other important metallic minerals, indicates that even on the economic score the granitic rocks are worthy of further attention. In addition it must be remembered that much of the agricultural areas is underlain by the granitic complex and now that it has been conclusively demonstrated that the minor elements play a very significant role in animal and plant nutrition a closer study of these rocks is well warranted because from them come the

mineral constituents of the soils. I would urge that when mineral deficiency problems are being studied in any particular area detailed geological surveys be undertaken together with petrological and chemical work on the rocks and that attempts be made to correlate such data with the results obtained from the plant and animal nutrition investigations. Failure to effect such correlation means that what is probably a very useful tool which may provide a short cut to the time-consuming methods at present practised, is being overlooked. In connection with such mineralogical investigations I feel that spectroscopic analysis of minerals separated from the underlying rocks would be invaluable in pointing to the nature of the deficient elements. Such work would undoubtedly yield data that would be useful in subsequent nutrition investigations in other areas and incidentally be useful in unravelling the history of the granitic complex.

As has been mentioned the weathered nature of outcrops is a difficulty that is encountered in inland Western Australia, but along the southern and south-western coasts excellent exposures of fresh rocks have been laid bare by marine erosion and close study of such exposures would yield much information about the Western Australian granitic rocks and the vexed question of granitization that has recently been so completely reviewed by Read (80).

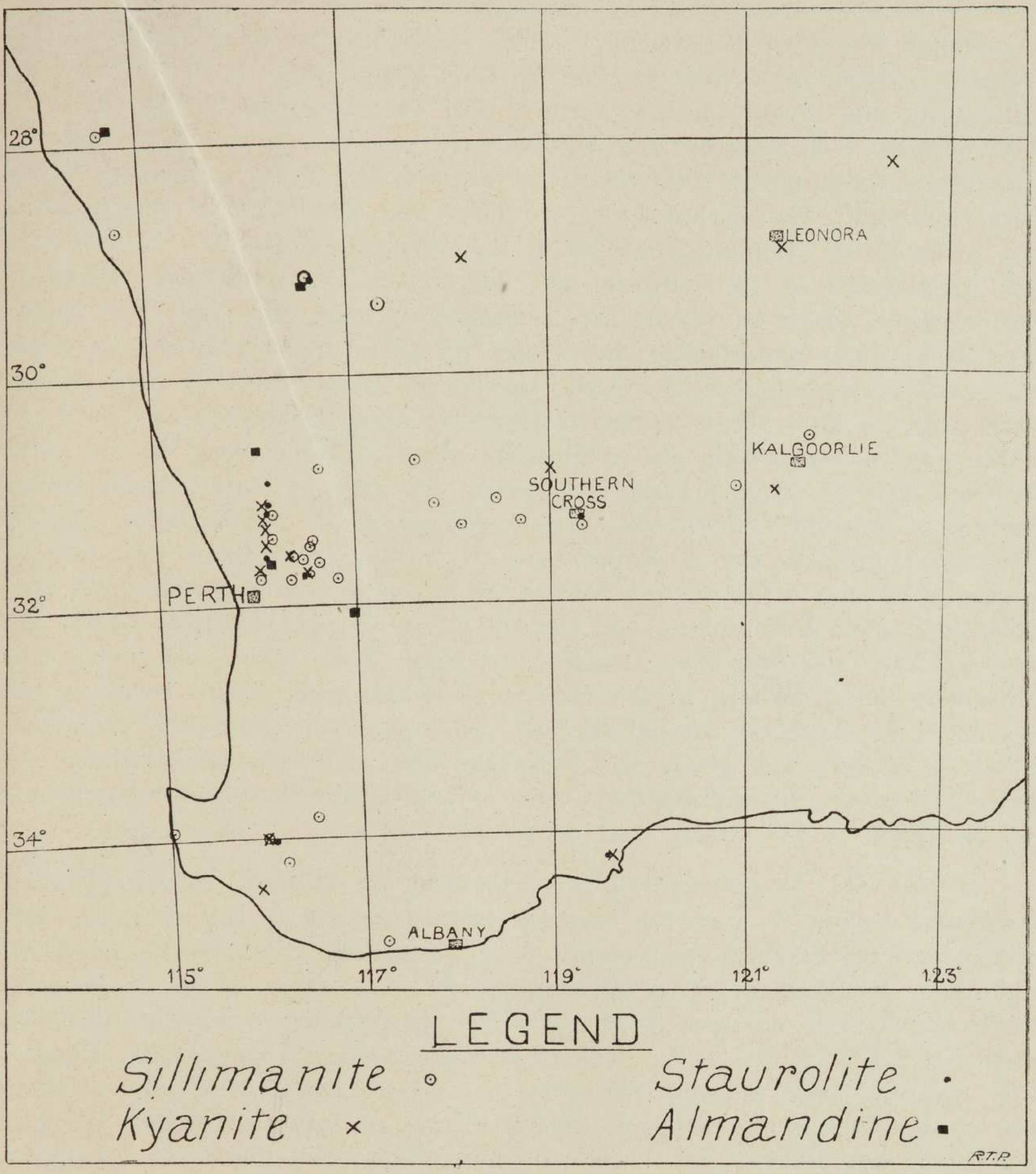
D. METAMORPHISM OF ARCHAEOZOIC ROCKS.

As has been indicated above the main period of orogenesis and constructive regional metamorphism was more or less contemporaneous with the emplacement of the Older Granites but in certain goldfields areas extensive regional and local metasomatism has been effective and earth movements of later age than the Younger Granites have brought about simple dynamic metamorphism of the older rocks. This latter is particularly noticeable in the granitic complex of the Darling Range near Perth, the rocks of which have, along numerous narrow shear zones, been converted into sericite schists as at Darlington (20, p. 174). This dynamic metamorphism is of comparatively late development being probably later than the Proterozoic basic igneous activity (20, p. 176) and will not be considered further here.

In view of the two markedly different types of metamorphism of Archaeozoic age it will be necessary to consider them separately thus:—

1. DYNAMOTHERMAL METAMORPHISM.

There is too little published petrographical information to allow of more than a very generalised account of regional metamorphism in Western Australia, a topic which has not, to my knowledge been previously discussed and I put forward these generalizations in the hope of provoking further inquiry. The detailed petrographic work that has been published has dealt with the more economically important greenstones, rocks, which although useful in a study of zonal metamorphism (100 and 70) do not yield such critical data as the pelitic sediments. Moreover the available petrographic data on the greenstones accumulated many years ago contains very few detailed optical data about the chlorites and amphiboles which are necessary if these greenstones are to be used as indicators of metamorphic grade (100).

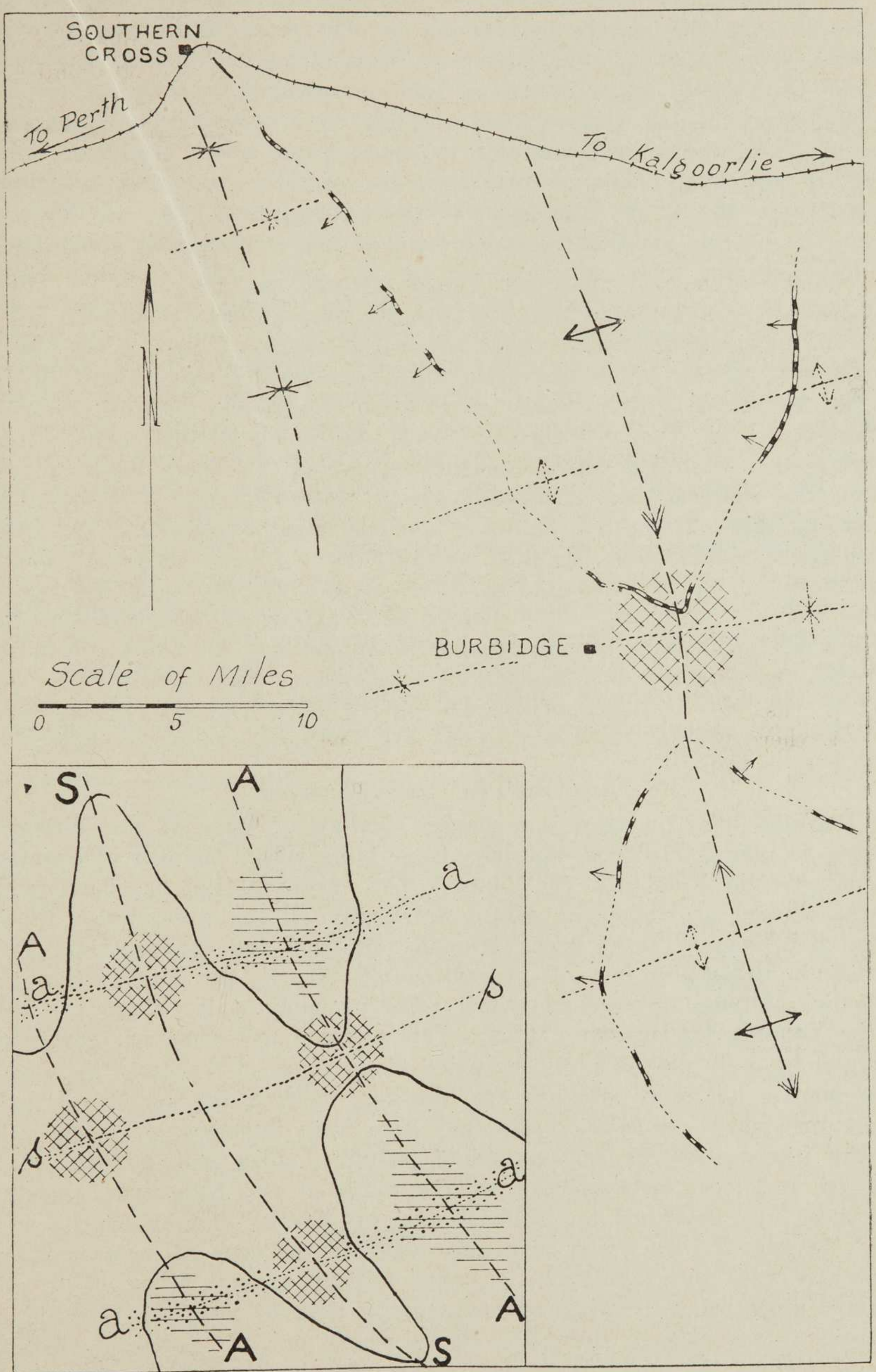


Text Fig. 3.—Sketch map of south Western Australia showing the known occurrences of the higher grade metamorphic index minerals (data from 88 and the rock collection of the Department of Geology of the University of Western Australia).

In dealing with regional metamorphism the southern half only of the State will be considered because of our almost complete ignorance of the petrography of the Archaeozoic formations in the northern part. As a starting point we may consider the known occurrences of the higher grade metamorphic index minerals in the southern part of the State. These occurrences are shown in Text fig. 3 and from their distribution it appears that the grade of metamorphism decreases from west to east. The more numerous occurrences of such index minerals towards the western margin of the Western Australia Pre-Cambrian shield may be partly due to these areas having been studied in more detail in certain parts than the goldfields areas which have been more broadly surveyed. Nevertheless from other considerations, as outlined below, I believe that the distribution of these index minerals as shown in figure 3 yields a true broad picture of regional metamorphism in the southern half of Western Australia, viz. that the grade of metamorphism decreases from west to east. A most noticeable feature is the high grade metamorphism of the Darling Range

and Yilgarn Goldfield rocks as compared with the very low grade metamorphism found at Kalgoorlie. The pelitic sedimentary phase of the Yilgarn-Kalgoorlie System in the Darling Range area is represented by sillimanite and kyanite-bearing schists and therefore belongs to the sillimanite zone. Sillimanite and kyanite are present in small amounts in the heavy fractions of soils from the Yilgarn Goldfield, sillimanite being more abundant than kyanite (27, p. 170) and Ellis (27, p. 68) records the presence of sillimanite schists in the Whitestone Series. In addition the greenstones of the Yilgarn are completely recrystallised schistose amphibolites which in places are garnetiferous and the jaspilites interbedded with the amphibolites have been completely recrystallised to banded quartz-magnetite-grunerite rocks similar to those of the Darling Range areas (68, p. 26). It is apparent therefore that the greater part of the Yilgarn area lies within the sillimanite zone. Farther east in the next exposed area of Yilgarn-Kalgoorlie rocks, the area extending from Bullabulling to beyond Bulong, the metamorphism is of much lower grade. Sillimanite gneisses are developed near the western margin of this area in a quarry alongside the railway line at the 332-mile peg approximately two miles west from Bullabulling and Carroll (9, p. 11) has recorded sillimanite and kyanite from the heavy residues of some soils from Bulong and Kanowna but elsewhere in the vicinity of Kalgoorlie, where there is an extensive development of pelitic and psammopelitic sediments, metamorphism is of very low grade and there has been no recrystallisation of the basic lavas and the sedimentary rocks which although as strongly folded as elsewhere in the State, are practically unaltered in character.

In the Mt. Margaret Goldfield according to Hobson (42, p. 16) "a noticeable feature is that the regional metamorphism is low in grade and almost entirely confined to dynamic or stress effects. Despite the relatively abundant development of sedimentary beds of a type which is usually fairly sensitive to changes in temperature and pressure conditions the only metamorphic minerals so far located in these beds are andalusite, chiastolite, staurolite and possibly corundum in several small occurrences, which are clearly due to the contact heating effects of local intrusions. A garnetiferous amphibolite has been recognised from the dump on 'Hutanui' G.M.L. 1679 but garnets are absent from the amphibolites elsewhere in the vicinity. Minerals such as kyanite and sillimanite are absent, as are also mica schists." Miles however (64, p. 10) has since described an occurrence of kyanite schist from the Camel Humps, approximately 33 miles north of Laverton. It is interesting to note that the Camel Humps kyanite-quartz schist and also the kyanite-andalusite-quartz schist of Mt. Leonora (64, p. 14) are comparatively close to the granitic and gneissic rocks (similar to the occurrence of sillimanite gneiss at Bullabulling in the Coolgardie Goldfield) and it appears that in these Central Goldfields areas the grade of regional metamorphism is high in the vicinity of the granitic gneisses and low in places remote from the granitic rocks. Kalgoorlie itself lies in the centre of an area of approximately 8,000 square miles of Yilgarn-Kalgoorlie System rocks (see 40) and although the formations have been very strongly (isoclinally) folded so that all dip, on the average, about 70° to 80° to the west, because of its remoteness from the granitic rocks the heat factor has been low and the rocks show no evidence of constructive metamorphism. Metasomatism, as discussed in the next section, has however produced marked changes in the rocks of the Kalgoorlie area.



Text Fig. 4.—Structural sketch map of the southern part of the Yilgarn Goldfield showing the outcrop of the metajaspilite horizon. The structure is a main NNW trending anticline overturned to the east and crossed by ENE crossfolds. *After Ellis* (27, plate 2). The area of most intense metamorphism in the vicinity of Burbidge (according to R. S. Matheson) is shown by crossbatching. Inset is a diagrammatic structural plan of such an area with main NNW trending anticlines (A) and synclines (B) with minor crossfolds (anticlines *a* and synclines *s*), showing the most favourable parts of such structures for gold deposition (dotted), intense metamorphism (crosshatched) and granitization (horizontally ruled).

It has recently been discovered that cross-folding on more or less east-west axes has been superimposed on the main north-west trending folds in the Central Goldfields areas. What affect has this cross folding had on the rocks? The influence of such crossfolding in forming loci for ore-deposition in the Yilgarn Goldfield has been described by Ellis (27, pp. 134-147), the most favourable locations being where the main N.W. trending anticlinal folds are traversed by easterly trending anticlinal cross-folds. Mr. R. S. Matheson of the Geological Survey of Western Australia informs me that he considers that the cross-folding along more or less east-west axes, superimposed on the main N.W. trending folds, has been an important factor, not only in the location of auriferous deposits but in determining the grade of metamorphism and also the degree of granitization to which the rocks have been subjected. Thus, according to him the most intense area of metamorphism in the Southern Yilgarn is in the vicinity of Burbidge (see fig. 4) where the structure consists of a main N.W. trending anticline crossed by an east-west synclinal cross-fold. He suggests that the more intense metamorphism of this area is due to the pressure being greater in such a structure than in structures such as anticlines crossed by anticlinal cross-folds. In the latter structure tension is the predominant force, leading to the formation of rock openings which have later been filled by ore solutions; in such areas granitization is more extensive than in the higher pressure areas where recrystallization of the rocks is the dominant process. These suggestions concerning the distribution of highly metamorphosed areas, granitized areas and the most favourable areas for ore deposition are illustrated diagrammatically in Text fig. 4.

2. METASOMATIC METAMORPHISM.

Regional metasomatism is a marked feature of some of the Western Australian mining districts, especially those lying within the belt of country extending from Kalgoorlie to Wiluna. This metasomatism has been most closely studied at Kalgoorlie where practically all the greenstones (both Older and Younger) have been regionally albitized and carbonatized. The process is essentially one of propylitization due to the introduction of carbonic solutions or vapours which were probably a late-stage product of the Younger Greenstone magma. This regional metasomatism has been followed by more intense local alteration along zones of weakness by somewhat similar but more siliceous ore solutions yielding the auriferous lode formations which are shear zones that have been intensely metasomatized by the introduction of carbon-dioxide, sulphur, silica and potash. The regional and local metasomatism of the rocks of the Kalgoorlie District has been fully described by Stillwell (91, pp. 50-59) and by Clarke and Ellis (18, pp. 781-785) who have also described the type of metasomatism associated with ore formation in other mining areas. Miles (67) has recently discussed the nature of metasomatic changes near the Corinthian ore-body in the Yilgarn Goldfield—effects which are only noticeable within several feet of the auriferous veins. This very localised type of metasomatism, which leads to the development of biotite in the schistose amphibolite country rocks appears to be the most common type of change in the vicinity of the auriferous veins of the Yilgarn Goldfield generally.

E. ORE FORMATION.

Considered from the economic viewpoint the most important result of Archaeozoic igneous activity in Western Australia has been the formation of the various ore deposits which have played an important role in the

economic development of the State. With but one or two exceptions all the primary metalliferous deposits in Western Australia were formed in Pre-Cambrian times as the aftermath of igneous activity and as there has been a number of distinct periods of such activity it is pertinent to inquire here regarding the relationship between ore deposition and such igneous activity. Simpson (87) has provided a lead in this connection by delineating the various metalliferous provinces and dealing with epochs of mineralization in the State, but I should like to set down a few additional observations, dealing especially with the auriferous deposits.

1. AURIFEROUS MINERALIZATION.

The distribution of the gold deposits has been dealt with by Simpson (87) and the geology of these deposits has been outlined by Maitland (56). Since the publication of Maitland's work there have been notable advances in knowledge of the relationship between structure and ore deposition and in recent years some of the mining areas have been re-surveyed, particular attention being given to structural considerations. The rock structure is undoubtedly a very important factor controlling the location of ore deposits but it is equally important that there be a source of mineralizing solutions. Simpson (87, p. 215) considers that the gold-bearing solutions were derived from granitic magma and this appears to be the general opinion of Western Australian geologists.

When however we look closely at mineral associations within the ore-bodies and the associated metasomatic phenomena it is evident that there are several very distinct types of ore deposit thus:—

(i) The sulphide-bearing lode formations associated with extensive silica-carbonate metasomatism of the country rocks as exemplified by the lodes of the Golden Mile at Kalgoorlie.

(ii) The auriferous quartz reefs, which although they may occur in similar country to (i) are characterized by very slight potash-silica metasomatism of the country rocks. The auriferous bodies of the Yilgarn Goldfield are typical. Closely allied to this type are the porphyry dykes traversed by networks of contemporaneous auriferous quartz veinlets as at the Tindals Mine, Coolgardie, and the Patricia Mine at Edjudina.

There must be some reason for such difference—either it is due to a different source for the ore-solutions or they must have travelled different distances from the parent source. Simpson (87, p. 215) considers that the "earliest gold veins, such as those of Kalgoorlie, Meekatharra and Wiluna are invariably closely connected with large porphyry dykes . . . . not associated with pegmatite veins, being characteristic of an earlier and hotter period of igneous intrusion, causing extensive metasomatism along the zones of fracture." At the same time Simpson considers that the ultimate source of all the gold was a granitic magma. I am inclined to the view that the sulphide-bearing lode-formations associated with extensive carbonate metasomatism of the country rocks are genetically related to the Younger Greenstone magma whereas the quartz reef type were most probably derived from some granitic magma. The suggestion that these lode formations are related to the greenstone magma is not a novel one since it was put forward in the first instance by Thomson (97, p. 670) but appears to have been overlooked by later authors. As has been noted earlier there has been a marked tendency to differentiation of the Younger Greenstone magma. This has lead to a sodic end-phase which in addition to yielding the albite porphyries has effected albitization of the greenstones and this in turn was followed by the activity of carbonic solutions

or vapours, representing a later product of the greenstone magma, which has caused widespread metasomatic changes in the earlier rocks of the series. The final stage of activity of the Younger Greenstone magma was the more intense or rather localized action of such carbonic solutions along shear zones bringing about the formation of the lodes. All investigators of Kalgoorlie geology are agreed that the ore-bearing solutions come from the same magma as the albite porphyries but some (41, p. 314) consider that these porphyries are offshoots from an underlying granite batholith. The genetic relation of the albite porphyries to the Younger Greenstone magma has been discussed previously and if such relation exists, as seems highly probable, then the Younger Greenstone period must be regarded as one of ore formation.

The auriferous quartz veins and porphyries, on the other hand, appear to be derivatives of a granite magma. Ellis (27, p. 149) considers that the auriferous quartz reefs of the Yilgarn Goldfield are related to the "granite magma which has intruded the folded rocks of the Yilgarn System as batholiths," i.e. the Younger Granite of this paper. It is interesting to note however that throughout the Yilgarn the auriferous quartz reefs are invaded by pegmatite dykes (27, p. 88) which appear to be the end-phase derivatives of the Younger Granite and this throws some doubt on the suggestion that the auriferous reefs are related to the Younger Granite. It may indicate that there were a number of distinct periods of Younger Granite invasion.

It is interesting to notice also that Matheson (61, p. 21) considers that the auriferous reefs of the Edna May Mine at Westonia were formed prior to the granitization (i.e. Older Granite period) of this belt of country. If this be so then it is evident that the Edna May reefs are much older than all of the granites.

It is evident therefore that our knowledge of the time relations of auriferous mineralization in Western Australia is very meagre. It is probable that there were at least two distinct periods, one related to the Younger Greenstone magma, the other in some way related to the granite intrusions of the late Archaeozoic. Both types may occur in the same area, thus at Kalgoorlie there are the lodes of the greenstone magma type developed on the Golden Mile and the distinctly different felspar porphyry dykes with auriferous quartz veinlets a few miles to the west near Binduli (45, p. 41) and a few miles to the south-east at Golden Ridge (56, p. 73). Because these two contrasted types occur within the same comparatively restricted area we should not be led immediately to the conclusion that they come from the same source.

2. NON-AURIFEROUS MINERALIZATION.

Metals such as silver, copper, arsenic and antimony are produced as by-products in the treatment of auriferous ores and so will not be considered here. All the important non-auriferous mineral deposits except those of iron, copper and lead appear to be genetically related to the Younger Granites. The economically important iron ores such as those of Yampi Sound (8) and Koolyanobbing do not appear to be of magmatic origin but to be metamorphosed sedimentary formations, and the copper and lead deposits some of which occur in post-granite rocks must, in part, be associated with a later period of activity than the granite. Lead deposits occur in Archaeozoic country rocks in the vicinity of Northampton and are regarded by Feldtmann (31, p. 26) as genetically related to the acid pegmatites of this area and thus to the granitic magma. Gibb

Maitland on the other hand considers the Northampton lead deposits to be related to the epidiorites (53, p. 8) which Feldtmann considers are older than the pegmatites (31, p. 27). Whatever be the parent source of these lead deposits, the lead fields of the North-West Natural Region indicate important lead mineralization of post-granite age.

The important deposits related to the Younger Granite include those of tin, tungsten, molybdenum, tantalum and niobium, beryllium, lithium, radioactive minerals and such minerals as mica and felspar. All these are confined largely to the end-phase pegmatites of the Younger Granite magma and the distribution of most of these has been described by Simpson (87). Simpson (81) considers these minerals do not as a rule occur in the orthoclase or microcline pegmatites associated with potash granites such as those of the Northampton or the Darling Ranges but are almost invariably to be found in the albite pegmatites associated with soda granites, such as are seen at Wodgina and Moolyella in the North-West or Ravensthorpe in the south. Speaking of the distribution of rare metals in Western Australia (82, p. 87) he says that "such pegmatites [albite pegmatites] are the typical homes of the rare alkali metals and the rare earth metals of the cerium and yttrium type, as well as tantalum, niobium, beryllium and uranium."

The present day development of new alloys incorporating many of these metals should lead to the more intensive exploitation of such deposits and stimulate the closer study of the granitic complex and in this regard spectoscopic analyses for the minor constituents of rocks of this complex in conjunction with detailed petrographic investigation would undoubtedly be of great economic and scientific value.

IV. PROTEROZOIC IGNEOUS ACTIVITY.

There are two phases of igneous activity in Proterozoic times (i) An earlier volcanic phase represented by various lavas and pyroclastics interbedded with the sediments of the Nullagine Series and (ii) a later hypabyssal phase represented by dolerite dyke and sill intrusions.

A. VOLCANISM OF NULLAGINE TIMES.

The Nullagine System is extensively developed in the northern half of the State where it unconformably overlies the metamorphic and granitic rocks. The System consists broadly of clastic sediments with interbedded lavas and tuffs and also contains doleritic sills. As far as can be gleaned from published data there is considerable variation in the succession from place to place. The most completely studied section is in the vicinity of Nullagine township and has been described by Maitland (55, pp. 120-130). The volcanic rocks include bedded amygdaloidal lavas, ash and agglomerate which occur at different horizons within the series. The section across the valley of the Nullagine River given by Maitland (55, plate 8) shows the occurrence of these volcanics at three horizons. Maitland states (55, p. 128) that wherever these volcanics have been examined it has been invariably found that they consist of acidic lavas and that each band consists of separate lava flows, each of no great thickness. Higher up in the series the conglomerates, sandstones, felsitic lavas and ash are overlain by limestones (plate XIII. of G.S.W.A. Bull. 33 shows a generalised section of the Nullagine Series in the West Pilbara) which is well exposed at Carawine Pool on the Oakover River. Here the limestones rest on basic

lavas (55, p. 26). It appears therefore that in late Nullagine times basic lavas were extruded. At Braeside the country rocks of the lead-bearing veins are a series of basic lava flows which are regarded by Finucane (34) as belonging to the Nullagine Series. These basic lavas contain interbedded limestones and are probably comparable to those at Carawine Pool. At Braeside the individual basic flows average about 80 feet in thickness, being fine-grained at the base of the flow, medium-grained at 20 or 30 feet above the base and highly amygdaloidal over the upper 20 feet. To the west of Braeside the basic lavas are overlain conformably by a considerable thickness of shales, sandstones and grits with occasional interbedded bands of volcanic ash and porphyry while to the east the basic lavas are overlain by "quartz porphyry and quartz-felspar porphyry flows" (34, p. 3).

Although from data at present available it is difficult to draw up a stratigraphical table for the Nullagine System it appears that, so far as igneous activity in the Pilbara region is concerned, it took place at intervals throughout Nullagine times, being volcanic and frequently explosive. The earliest eruptions were acidic, giving way to basaltic eruptions in middle Nullagine times and towards late Nullagine times again becoming acidic and of explosive character.

The Nullagine Series is also widespread in the North Kimberley. Over the greater part of this region the outcropping rocks consist of basaltic lava flows interbedded with massive sandstones of Nullagine age which are either horizontal or gently folded. Maitland (52, p. 9) refers to the igneous rocks as "a series of bedded and intrusive igneous rocks, the prevailing types being andesite, dolerite and diabase . . . . beds of volcanic ash and breccia are common in certain localities," and he considers that some at least of these basic rocks are sills. Edwards (25) has recently described all the available basaltic rocks from the North Kimberley and has distinguished a number of sub-groups which however are all of tholeiitic type. There appear to be two main groups: (i) the fine-grained interbedded basaltic rocks which tend to be andesitic in character and (ii) the coarser dolerites which may probably be from the dolerite dykes which intrude the lavas (52, p. 9).

The felsitic lavas which are so common in the Nullagine Series in the North-West region do not appear to be developed in the North Kimberley region.

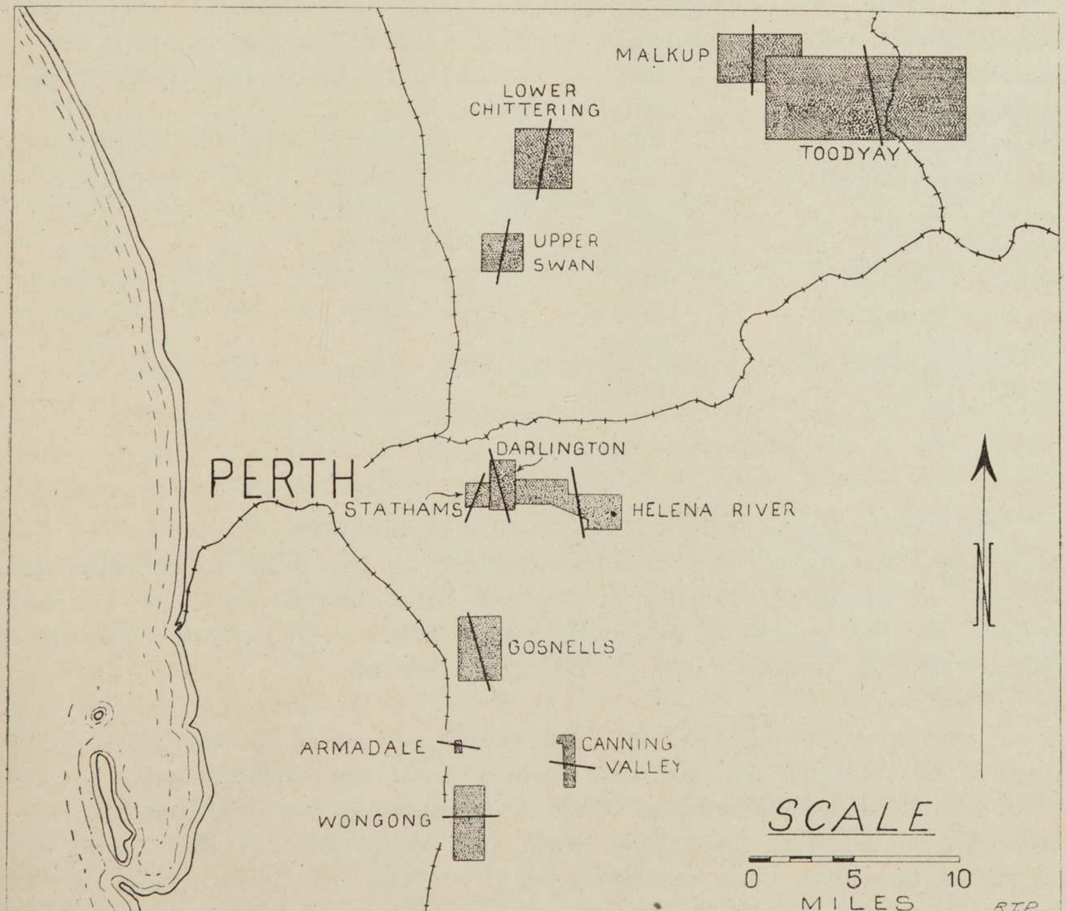
The Nullagine Series is also developed in the Warburton Region. Forman (39, p. xxiv.) now considers that the base of the Nullagine System in this area should be placed below the Warburton Range porphyries. Therefore in this area we have the earlier Proterozoic felsitic flows or sills similar to those of the Nullagine Series of the Pilbara. Higher in the succession in the Warburton Range area volcanism is represented by altered basaltic lavas (94, p. 135) probably belonging to the same stage of the Nullagine as the basaltic lavas of Braeside in the Pilbara (34).

The Nullagine Series in the south-western part of the State is thought to be represented by the Stirling Range beds and the Cardup Series. The Stirling Range beds contain no evidence of contemporaneous igneous activity. The Cardup Series at Armadale and various other localities along the Darling Scarp contains a conformable albite epidiorite sill or flow (74, p. 43) which is regarded as being older than the dolerite dykes

of this area. Since it shows a comparable grade of metamorphism to the associated sediments it is probably older than the earth movements which have affected the Cardup Series.

B. LATE NULLAGINE DYKE INTRUSIONS.

Throughout the State wherever Pre-Cambrian formations are developed there is a series of quartz dolerite dyke intrusions which traverse all the previously considered formations including the Nullagine Series, as in places they can be seen intruding the basic lavas of the Nullagine Series, e.g. at Braeside (34, p. 5). These basic intrusives have nowhere been found to penetrate the Palaeozoic formations but, in the Kimberley Division they may have been the feeding channels for the Cambrian lava flows. This possibility is considered in a later section of this paper. In the South-West part of the State the only evidence regarding time of intrusion of these quartz dolerites is that they are later than the granite and also intrusive into the Cardup Series (74, p. 31) and the Stirling Range beds (102, p. 92), while in the Central Goldfields they are post-gold and for this reason have not been closely studied since they do not in any way affect the tenor of ore-bodies.



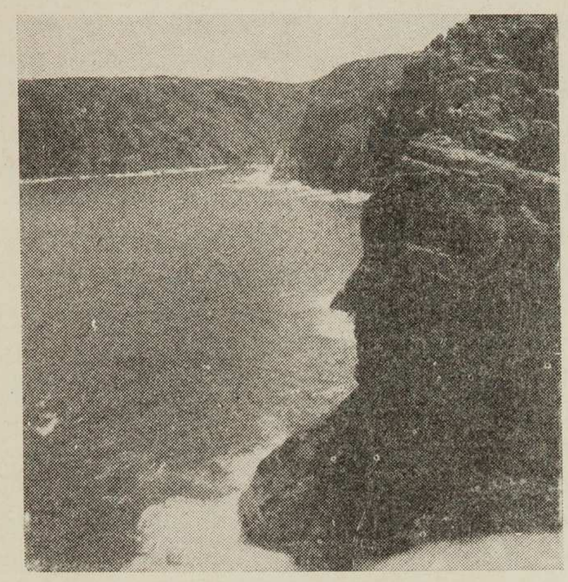
Text Fig. 5.—Sketch map showing areas in the Darling Range which have been mapped in detail and the average trend of the quartz dolerite and epidiorite dykes. In general the dykes trend in a northerly direction but note the marked change to an east-west trend in the country to the south of Armadale.

Manifestations of this period of igneous activity are particularly well developed in the Darling Range area and it is in this region that they have been most closely studied. The dykes here form a well-defined swarm which in the northern parts of the range have a N.N.E. trend, in the centre a northerly trend and towards the south an E.S.E. trend. Near Perth these dykes have been quarried for road metal and the quarries so opened up indicate that the dykes dip steeply either to the east or to the west. Up to the present they have been mapped closely in eleven rather discontinuous areas, with a total area of 100 square miles only, so that until these surveys have been extended to embrace a wider area no definite statement can be made concerning their tectonic significance. They appear however to be related to an uparching of the Pre-Cambrian shield with the development of steeply dipping tensional fractures along which the basic magma has arisen. The amounts of crustal stretch due to dyke intrusion in the various areas near the Darling Scarp that have been mapped in detail are seen in the following table in which the areas are arranged from north to south. (See text Fig. 5).

"Area" and Reference.	Breadth Examined.	No. of Dykes.	Average Trend.	Aggregate Thickness. of Dykes.	Amount of Crustal Stretch.
	chains.			chains.	
Lower Chittering (63) ...	160	16	N. 10° E.	18	1 in 8·9
Upper Swan (37)	200	15	N. 10° E.	16	1 in 12·5
Darlington (20)	160	24	N. 15° W.	18	1 in 6·7
Helena River (6)	400	24	N. 10° W.	20	1 in 20·0
Stathams (unpublished) ...	80	6	N. 25° E.	11	1 in 7·3
Gosnells (22)	110	10	N. 10° W.	12	1 in 8·2
Armadale (74)	60	7	N. 80° W.	$7\frac{1}{2}$	1 in 8·0
Canning Valley (6)	280	15	N. 80° W.	21	1 in 13·3
Wongong-Cardup (95) ...	346	11	W.	22	1 in 15·7
Malkup (21)	400	24	N.	27	1 in 14·8
Toodyay (76)...	960	24	N. 10° W.	44	1 in 21·8

The Toodyay and Malkup areas are situated farther inland than the other areas mentioned and have been added to the table to indicate the tendency of the dyke intensity to decrease with distance from the Darling Scarp. In the goldfields and wheat belt areas still further east these dykes, although present, are not nearly so abundant.

A rather remarkable feature of the geology of the south-west part of the State is the absence of this dyke swarm from the country lying to the west of the trough extending from Geographe Bay to Flinders Bay. Although considerable geological work has been done in this area, no dolerite dykes have been encountered. Professor Clarke and Mr. H. T. Phillipps inform me that these dykes are also scarce in those parts of the coastal areas extending from Nornalup to Doubtful Island Bay which they have examined, but near West Cape Howe the coastal cliffs which in places rise approximately 200 feet almost vertically from the sea (Text Fig. 6), are composed of this dolerite which seems to lie on a basement of



Text Fig. 6.—Dolerite forming coastal cliffs approximately 200 feet high at West Cape Howe on the south coast some 20 miles west from Albany.
Photo—H. T. Phillips.

gneiss—this extensive outcrop, probably the largest yet noted of the quartz dolerite, appears to be a sill but the cliffs are too inaccessible for any detailed examination.

Petrographically the rocks of this period are nearly everywhere normal quartz dolerites (or gabbros) which, while generally unaltered, may in places be partially uralitised. Petrographic details of these rocks have been given in various publications (74, pp. 44-8; 76, pp. 125-7; 25, pp. 82-3) and Fletcher (36) has considered the petrology of the basic dykes of the South-West in some detail.

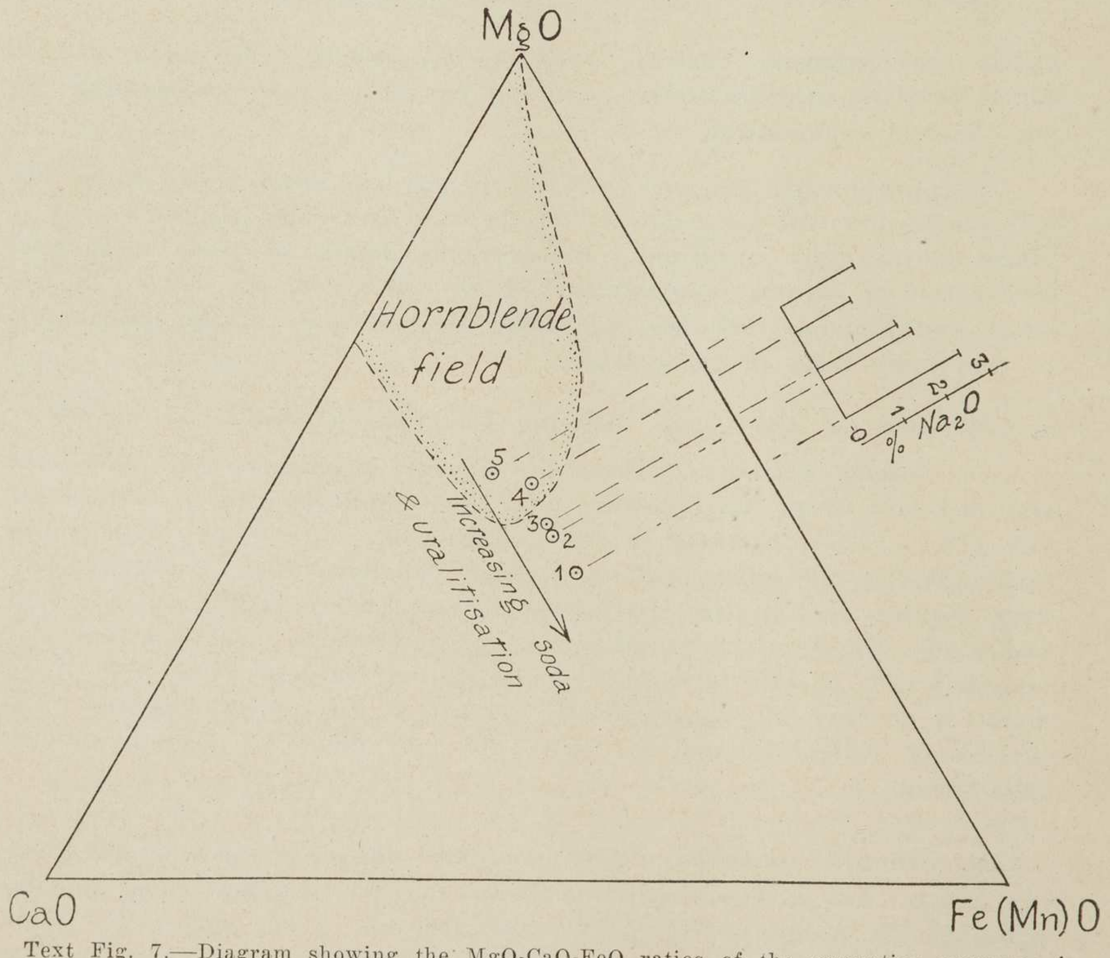
Members of the group differing from the normal type include:—

(i) *Olivine dolerites*: These are of rare occurrence and have been recorded only from the following localities:—Norseman (7, p. 29), Toodyay (76, p. 127), Newfield in the Yilgarn G.F. (65), Pope's Hill Siding approximately 60 miles north-west from Southern Cross (unpublished), near Bentley Hill in the Warburton Region (94, p. 182), and Pt. Irby and Point Hood on the south coast (unpublished). Simpson has also recorded (86, p. 116) a fayalite gabbro from Burge's Find but it is doubtful whether this is genetically related to the quartz dolerites. The picrites of Kalgoorlie and St. Ives (28) may belong to the olivine dolerite group.

(ii) *Biotitic epidiorites*: Very rare and only recorded from the Darling Scarp (74, p. 46) where they occur in narrow dykes or as an edge phase of the epidiorite dykes described below.

(iii) *Epidiorites*: These are abundantly developed in the Darling Scarp area within a radius of approximately 10 miles from Darlington. Outside this area the rocks are either uralitised quartz dolerites or unaltered quartz dolerites. These epidiorites differ from the dolerites in that blue-green hornblende is developed to the exclusion of pyroxene—the

reason for this development of hornblende in this particular area is not apparent. A plot of the MgO-CaO-FeO ratios of the available analyses of dolerites and epidiorites of the Darling Range near Perth by the method outlined by Kennedy (49) is shown in Text Fig. 7. The least uralitised rock No. 5 (from Toodyay) lies within the hornblende field, that containing blue-green hornblende to the exclusion of pyroxene No. 1 (from Smith's Mill) lies most distant from the hornblende field. This indicates therefore that the basic oxide ratios have not been responsible for the crystallization of the hornblende. In addition Kennedy has noted (49, p. 207) that the presence of water alone cannot control the nature of the ferromagnesian crystallization. The few available analyses seem to indicate that with increasing uralitisation there is an increase in the alkali (especially soda) content as indicated in Fig. 7, so that this process should be more marked in the later crystallizing rocks of this suite. In the epidiorite area within a 10-mile radius of Darlington, there appears to have been a recrystallization of the uralite to blue-green hornblende and the fact that soda has entered into the hornblende is seen in the stronger bluish-green colour at the borders of the hornblende prisms. Another characteristic of these epidiorites which is shared to some extent also by the uralitised dolerites, is the presence of smoky felspars which according to MacGregor (51) indicates that the enclosing rock has been



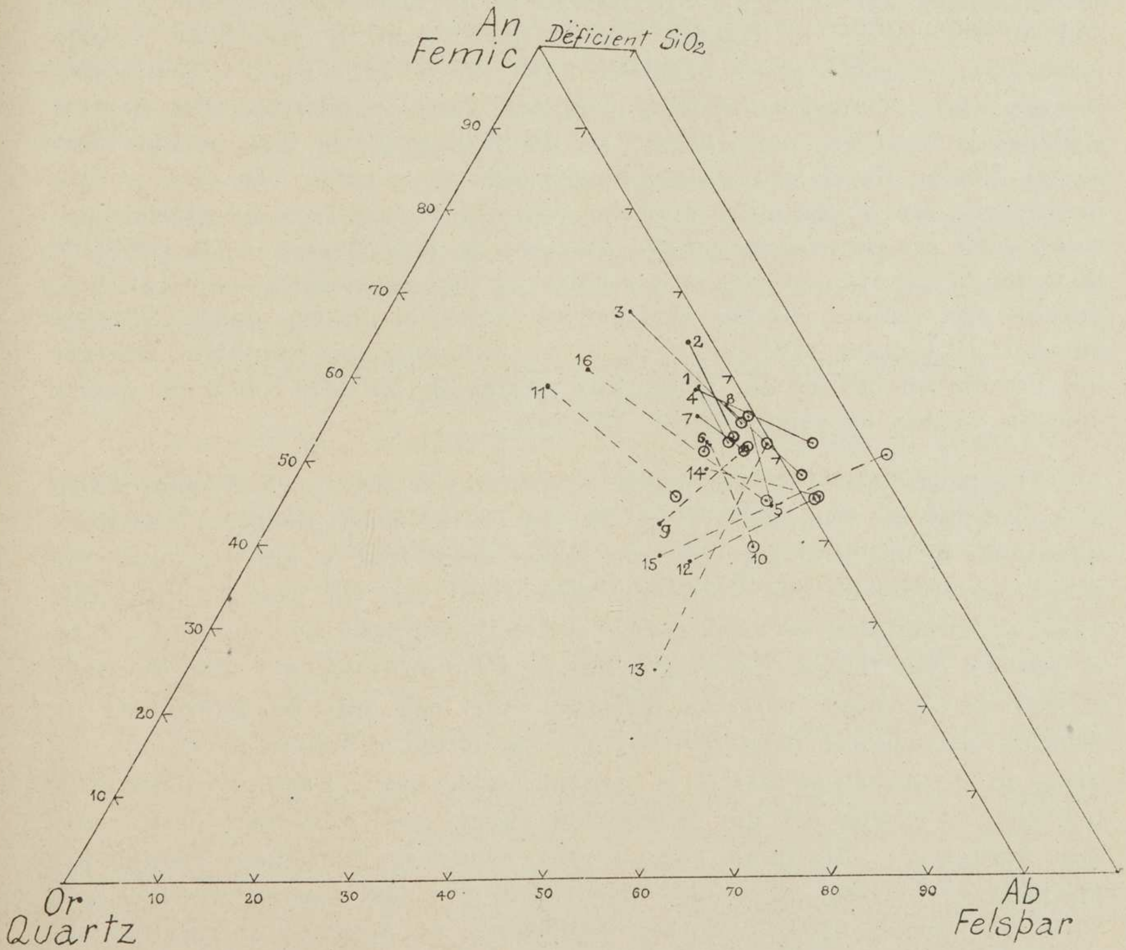
Text Fig. 7.—Diagram showing the MgO-CaO-FeO ratios of the normative pyroxene in the quartz dolerites and epidiorites of the Darling Range near Perth, and their relationship to the hornblende field (49). Insert is variation diagram of Na_2O plotted against distance from the hornblende field. 1, Epidiorite, Smith's Mill (83, p. 28); 2, Epidiorite (fine-grained), Bickley Brook (20, p. 173); 3, Epidiorite (coarse-grained), Bickley Brook (20, p. 173); 4, Uralitized quartz dolerite, Armadale (74, p. 45); 5, Quartz dolerite, Toodyay (76, p. 127).

contact metamorphosed. To my knowledge there are no post-epidiorite intrusions in this area and the presence of smoky felspars in these rocks does not appear to be explicable by contact metamorphism. Further work especially on the chemical composition of the pyroxenes and amphiboles and on the smoky felspars, is necessary before the origin of these epidiorites is completely known—they are however closely related to the quartz dolerites. The chemical characters of the quartz dolerites and related rocks are illustrated in Text Fig. 8.

C. IGNEOUS ROCKS OF UNKNOWN AGE.

In the southern half of the State dyke intrusions have been noted which do not appear to be related to the quartz dolerites just mentioned. All that can be said of their age is that they are post-gold or post-granite. They include:—

(i) *Norites.* These have been recorded from a number of widespread localities thus:—Norseman (7, p. 24) in the Dundas G.F., Barloweerie Peaks (11, p. 64) in the Murchison G.F., Ora Banda (47, p. 112) in the



Text Fig. 8.—**Late Nullagine Quartz Dolerites**—Larsen triangular diagrams (50) of rocks which appear to belong to the late-Nullagine hypabyssal activity. Circles are quartz-felspar-femic ratios, dots are or-ab-an ratios. The connecting lines are shown full for the rocks from the southern part of the State and broken for those from the northern parts of the State. Note that there appears to be more uniformity in the rocks of the southern part of the State than in the northern part. 1, Epidiorite (coarse centre of dyke), Bickley Brook (20, p. 173); 2, Quartz dolerite, Toodyay (76, p. 127); 3, Uralitized quartz dolerite, Armadale (74, p. 45); 4, Biotite epidiorite, Armadale (74, p. 49); 5, Epidiorite, Smith's Mill (83, p. 28); 6, Quartz dolerite, Morawa (84); 7, Gneissic epidiorite, Lower Palinup River (84); 8, Epidiorite, Mt. Singleton (84); 9, Dolerite, Mt. Holmes (83, p. 34); 10, Dolerite, Nullagine (83, p. 46); 11, Tachylite (selvage to dolerite dyke), Poona (83, p. 32); 12, Two-pyroxene quartz dolerite, Upper Prince Regent River (83, p. 22 and 25, p. 88); 13, Two-pyroxene dolerite, Synnott Creek (83, p. 22 and 25, p. 88); 14, Dolerite, Irregully Creek (83, p. 32); 15, Two-pyroxene dolerite, Mt. Lyell (83, p. 32 and 25, p. 88); 16, Two-pyroxene quartz dolerite, near F.B. 66, North Kimberley (25, p. 88).

Broad Arrow G.F., Fraser's Range (58, p. 8), and the Cavenagh and Blackstone Ranges (94, p. 132 and 178) in the Warburton Region. Simpson (101, p. 51) considers that a rock from Cue which had previously been regarded as a norite, is actually a gabbro.

The norites of the Warburton Region occur in three large patches in the granitic gneisses, the total area of norite probably exceeding 160 square miles (94, p. 96) and the main type appears to be olivine norite. Thomson, who was the first to describe these rocks, considered them to be related to the quartz dolerite magma and also to the norites of Norseman (96, p. 311) and in this is followed by later writers. The Warburton norites are intruded by basaltic dolerites (94, p. 97) [in the sketch plan given by Talbot and Clarke olivine norite is indicated as "gabbro"]. Talbot and Clarke (94, p. 96) note that some doubt is thrown on their observation of the relative ages of norite and basaltic dolerite, by petrological evidence, since the basaltic dolerites are more altered than the olivine norite. In my opinion the alteration of the basaltic dolerite is a deuteric effect and is in no way related to dynamothermal metamorphism and in the vicinity of Dangin (78) I have found a somewhat similar petrological example where perfectly fresh charnockitic rocks (hypersthenites etc.) are intruded by strongly uralitised basaltic dolerites. Petrological evidence is therefore not contrary to the field evidence that in the Warburton Region the dolerites are younger than the norites. In view of this pre-dolerite age of the olivine norites and of the occurrence of charnockitic rocks such as garnet-hypersthene gneisses in this Region it is probable that the Warburton norites are related to the charnockitic suite of pre-granite age (similar to the charnockitic xenoliths in the older granitic gneisses at Dangin (78)). It is, in my opinion, very doubtful whether the Warburton norites are genetically related to the late-Nullagine quartz dolerite magma as suggested by Thomson.

The most typical of the norite occurrences is that of Norseman which is considered by Campbell (7, p. 24) to be the most recent of the dyke intrusions in the Dundas G.F.—it varies from half a mile to one mile wide and traverses the Norseman area from east to west. Within this dyke all gradations between norite and hypersthenite are present and it is possible that this is due to gravitative differentiation and that the dyke is perhaps a rather flat-lying intrusion—this can only be determined by detailed petrological investigation of rocks from different parts of the dyke, an investigation that is at present under way. Further comparative petrological studies of the Warburton range and Norseman norites are also desirable. Maitland (59, p. 82) considers that these norites are probably of Tertiary age. This question is discussed further when dealing with the igneous activity of the Kainozoic. It appears to me that the norites are best regarded as Pre-Cambrian.

(ii) *Picrites.* An interesting occurrence of porphyritic olivine picrite has been noted by Farquharson from south of the Golden Mile at Kalgoorlie (28, p. 28). He considers that this occurrence is a picrite dyke rather than an olivine basalt flow and that it is younger than the albitic porphyry and therefore the youngest intrusive in the Kalgoorlie area (*loc. cit.* p. 33). The only other locality in Western Australia where this type of rock is known to occur is St. Ives (28, p. 31) where it occurs in a dyke intruding the greenstones (13, p. 13). In the St. Ives District

there are also dykes of the Norseman norite mentioned above and it is probable that there is some genetic relationship between the norites and picrites. As noted above the age of these dykes cannot be definitely fixed, but they are best regarded as Pre-Cambrian. It is probable that the Kalgoorlie and St. Ives picrites, the latter having been originally described by Farquharson (13, p. 13) as an olivine dolerite, belong to the earlier more basic olivine dolerite phase of the late-Nullagine quartz dolerite magma.

(iii) *Lamprophyres*: These have been noted at Cue, Paynesville, Leonora, Murrin Murrin, Mt. Morgans, Eulaminna, Wiluna and the Cavenagh Range. The petrography of this group has recently been dealt with by Miles (69) who finds that kersantites, augite minettes, hornblende and augite camptonites are represented in the known occurrences. No information is available regarding their age other than they are intrusive into the Archaeozoic metamorphic rocks.

(iv) *Serpentines*: Some occurrences of serpentinised ultra-basics may be later than the Younger Greenstone Series to which many of the ultrabasic rocks, as previously indicated, are undoubtedly related. Such a serpentine dyke has been described from Toodyay (76, p. 128).

(v) *Phonolite* (discredited) has been recorded from the South end of Parker's Range in the Yilgarn Goldfield (27, p. 85). As other nepheline-bearing rocks are unknown in Western Australia I re-examined this specimen, for the loan of which I am indebted to the Government Geologist, Mr. F. G. Forman. Re-examination shows that the mineral mistaken for nepheline is an untwinned oligoclase and that the rock is not a phonolite but a much altered porphyrite.

D. METAMORPHISM ASSOCIATED WITH PROTEROZOIC IGNEOUS ACTIVITY.

The rocks of the Nullagine System show very little sign of constructive metamorphism, the grade of metamorphism everywhere being very low. Perhaps the highest grade of regional metamorphism is to be found in the chlorite zone pelites of the Stirling Range and in the economically important crocidolite (blue asbestos)—bearing rocks of the Hamersley Ranges. Miles considers that the development of crocidolite in the banded ironstones of this region is due to recrystallization of material already present in the ironstones, under conditions of mild load metamorphism (66, p. 37) and that igneous intrusions have not been responsible for its formation (*loc. cit.* p. 35).

Contact metamorphism in the vicinity of the dolerite dyke intrusions has been noted in a few places only. At Armadale, biotite and chloritoid have been developed in the slates as a result of contact metamorphism by epidiorite and dolerite intrusions (74, p. 43). At Soanesville in the Pilbara, asbestos deposits occurring in serpentine at the margins of intrusive dolerite dykes are considered by Blatchford (1, p. 47) to be contact deposits due to the dolerite dykes. The Silversheen Asbestos deposits located 120 miles South-East from Onslow also, owe their origin to the contact effect of the intrusive dolerites which have caused the development of high grade chrysotile deposits in the dolomitic limestones of Nullagine age. Matheson (62) considers that the ochre deposits of the Ophthalmia Range are due to the contact alteration of hematite-bearing metasediments by intrusive quartz dolerite. This alteration, noticed only near the contact of the quartz dolerite and the metasediments, involves the change of specular hematite of the

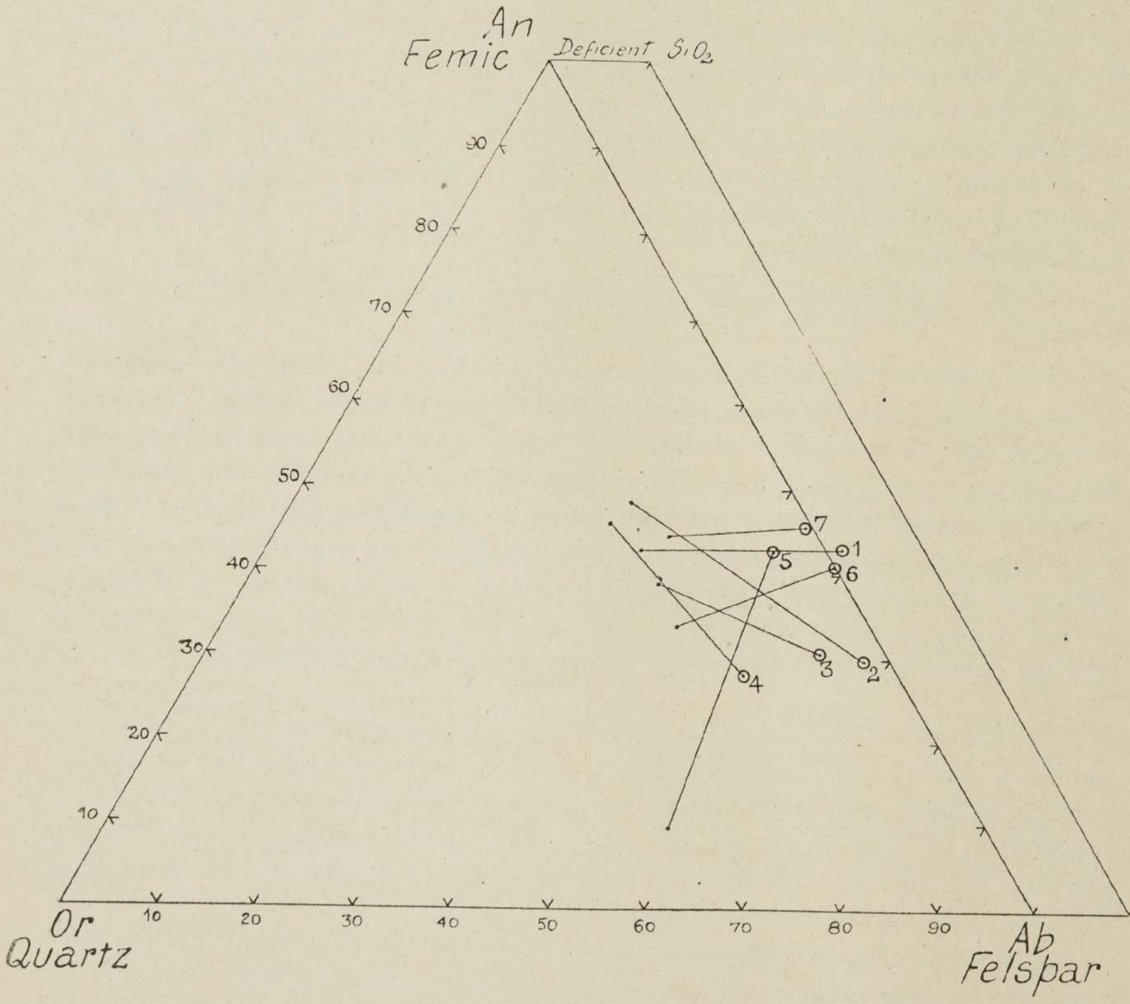
metasediments to ochreous hematite. It has not been effected by weathering, which has the effect of changing the hematite to limonite, the presence of which detracts from the quality of the ochre.

E. ORE-FORMATION ASSOCIATED WITH PROTEROZOIC IGNEOUS ACTIVITY.

In contrast to the auriferous metallization of the Archaeozoic, metallization of the Proterozoic formations was entirely of the base metal type. The most important examples of mineralization of the Nullagine rocks are the lead deposits of Braeside (34) and the copper deposits of Whim Creek (2 and personal communication from R. S. Matheson). Other lead and copper deposits of minor importance and similar nature occur at various localities in the Pilbara region and it is considered that all these deposits are genetically related to the Proterozoic basic magma (87, p. 218).

V.—CAMBRIAN VOLCANISM.

Igneous activity that can definitely be assigned to the Cambrian period is limited in its occurrence to the northernmost part of the State. Basaltic outflows of this period cover extensive tracts in the Antrim Natural Region



Text Fig. 9.—**Cambrian Basalts**—Larsen triangular diagrams (50). Circles are quartz-felspar-femic ratios, dots are or-ab-an ratios. 1, Olivine basalt, Fish Pool (26, p. 86); 2, Felspar basalt, Hearten's Homestead (26, p. 87); 3, Aphyric basalt, Negri River (26, p. 89); 4, Quartz basalt, near Hardman Range (26, p. 89); 5, Quartz basalt, "The Seven Mile" near Wyndham (26, p. 89); 6, Sub-ophitic basalt, Flora Valley Station (26, p. 89); 7, Aphanitic basalt, Martin's silver-lead mine (26, p. 89). Note that No. 5 does not appear to belong to the suite. Professor Clarke (who collected this specimen) informs me that he has always had some doubt as to whether or not this specimen was a Cambrian basalt.

of the North-East Kimberley and extend into the Northern Territory. They are reported to attain a thickness of as much as 3,000 feet in some localities. The occurrence and petrology of these basalts has recently been described by Edwards and Clarke (26) who have set down all the available field information and described all the specimens that have been collected from these flows. The basalt flows are practically horizontal and in places (in the Negri River area) are overlain by agglomerates and bedded tuffs which in turn are overlain by Cambrian limestones. Basalts of the Antrim Plateau are regarded by Clarke (26, p. 84) as lying above the Cambrian limestones rather than below them as in the Negri River, suggesting that there were two distinct periods of volcanicity. Petrologically they form a single series ranging from olivine basalts to quartz basalts and have distinct affinities with the tholeiitic magma type and in this they are similar to the quartz dolerite dykes discussed in connection with Nullagine activity. Edwards (25, p. 87) considers that although the Nullagine basalts of the North Kimberley resemble, in their chemical composition, those of the East Kimberley, "the varieties of basalt known to occur in the two regions cannot be matched." It seems probable however that the quartz dolerite dykes which intrude the Nullagine basalts represent a hypabyssal phase of the Cambrian volcanism —that they were the channels through which the extensive Cambrian flows were erupted. The available chemical analyses of the Cambrian basalts are shown graphically in Text Fig. 9.

The Cambrian period was then a period of igneous activity which began with the fissure eruptions of Lower Cambrian times. The hypabyssal phase of these extrusions is probably represented by the quartz dolerite dykes of the North Kimberley and of the southern part of the State from which all traces of the surface extrusions, if, indeed the magma ever reached the surface in these areas, have been removed by erosion. After the comparatively quiet fissure eruptions there appears to have been later explosive activity yielding the overlying agglomerates and tuffs (none of which appear to have been petrologically examined). In mid-Cambrian or even later times there may have been a further outburst of basaltic lava from the same magma as that yielding the Lower Cambrian flows.

This brings to a close the fairly continuous sequence of igneous activity which began in the early Archaeozoic. From Cambrian times onward, Western Australia was a very stable area and was not subjected to extensive earth movements or igneous activity except for small scale volcanism in Tertiary times.

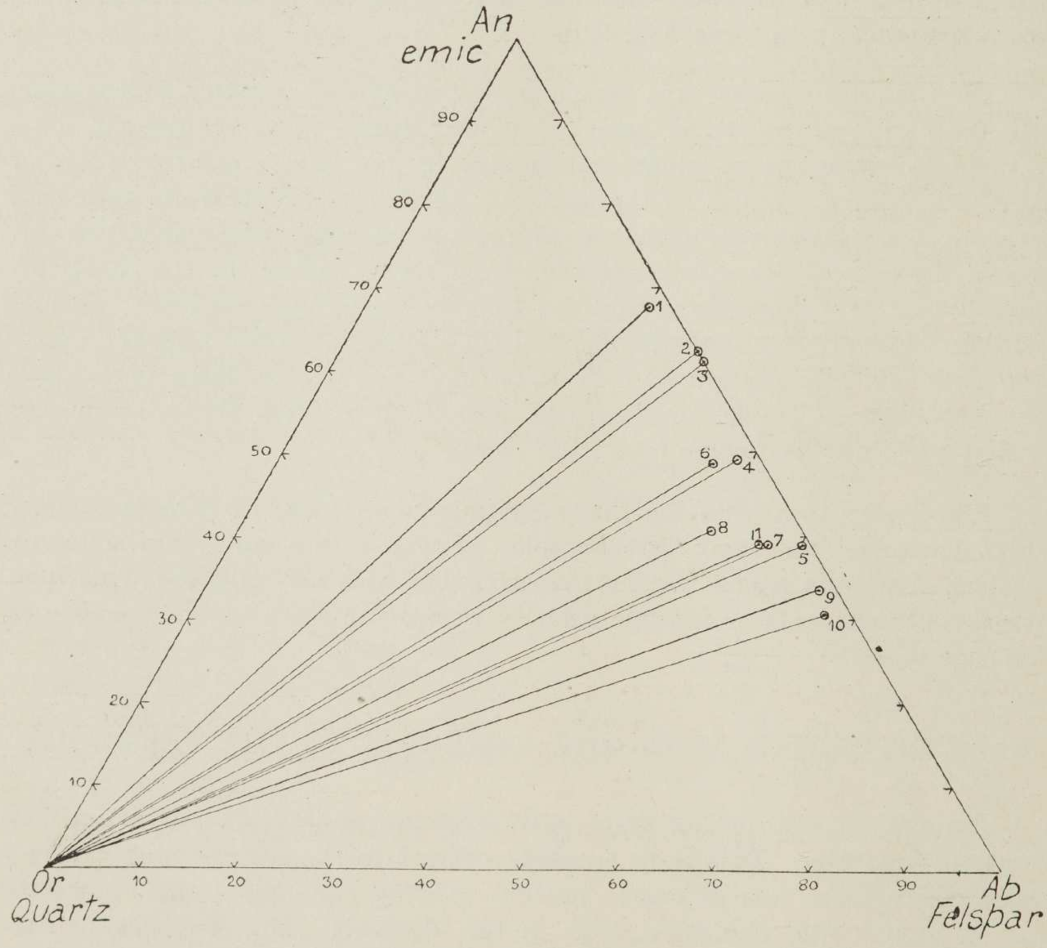
VI.—THE PERIOD FROM THE CAMBRIAN TO THE TERTIARY.

Throughout this period there is no evidence of any igneous activity in Western Australia. This is in marked contrast to the eastern part of Australia where there was extensive igneous activity throughout the Palaeozoic and on a somewhat decreased scale in the Mesozoic The economically important metallogenic epochs in eastern Australia with the exception of Broken Hill) are, as a consequence, much more recent than those of Western Australia. In eastern Australia the most important period of ore-formation was associated with the granite and granodiorite intrusions of Devonian times whereas in Western Australia, as we have seen, the late-Archaeozoic

was the main period of ore formation, and the late-Proterozoic the period when the less important non-auriferous base-metal deposits were formed.

VII.—KAINOZOIC VOLCANISM.

Two markedly different types of volcanism took place comparatively late in the geological history of Western Australia. These were the short-lived explosive lamproite eruptions of the Fitzroy Valley in the Kimberley and the comparatively quiet outpourings of basalt in the lower South-West. In neither case is it possible to assign these eruptions to a definite period. Mt. Yates in the East Kimberley approximately 60 miles due south from Wyndham is a volcanic plug intrusive into Nullagine (Proterozoic) quartzites (26, p. 85). In view of the preservation of this plug protruding through the Nullagine quartzites, Professor Clarke (personal communication) considers that it may probably be of Kainozoic age. Unfortunately however all the available specimens from this plug are too weathered to be of any use for determination of the type of rock (26, p. 85). Heavy mineral analyses of these rocks recently made in the Geology Department of the University of Western Australia showed no remnants of any original minerals.



Text Fig. 10.—**Kainozoic Leucite Lamproites**—Larsen triangular diagrams (50). Circles are quartz-felspar-femic ratios, and in all rocks of this suite the normative felspar is 100% orthoclase. 1, Carbonated wolgidite, Wolgidee Hills (99, p. 75); 2, Coarse fitzroyite, Mt. North (79); 3, Wolgidite, Mt. North (99, p. 75); 4, Cedricite, Mt. Gytha (99, p. 75); 5, Fitzroyite, Mamilu Hill (79); 6, Olivine-leucite lamproite, Mt. North (79); 7, Mamilite, Mamilu Hill (79); 8, Fitzroyite, Dadja Hill (99, p. 75); 9, Cedricite, Mamilu Hill (79); 10, "Fine-grained wolgidite," "P" Hill (79 and 99, p. 75); 11, Mamilite, Hill's Cone (99, p. 75).

A. LAMPROITES OF THE FITZROY VALLEY.

In the Fitzroy valley in the West Kimberley nineteen small, much dissected volcanoes have been located. These volcanic occurrences are in the form of circular or oval plugs occupying gas-drilled pipes which have penetrated the Permian strata of the Desert Artesian Basin. The only direct evidence of age of this activity is that the plugs are intrusive into the Upper Ferruginous (Liverynga) Series of the Upper Permian, but other evidence such as the preservation of the structure of the plugs makes it likely that they are no older than the Kainozoic. The volcanic rocks of these plugs belong to the rare group of lamproites and comparable rock types have been located only at the Leucite Hills, Wyoming, U.S.A. The occurrences and petrology have been described by Dr. Wade and myself (99) and I have recorded further details regarding the petrological structure of the vents in an unpublished Mss. (79).

The rocks consist of various associations of altered leucite with diopside, titaniferous phlogopite and potash-magnesia amphibole, and have yielded two new minerals, magnophorite (the potash-magnesia amphibole) and wadeite (a potassium-zirconium silicate) (71). Both massive lamproite and lamproite breccias are developed but the breccias are considered to be of non-extrusive origin rather than sub-aerial pyroclastics. All of the rocks examined are undoubtedly co-magmatic and the magma from which they were developed was of peculiar character and is considered to be genetically related to a mica-peridotite parent, the lamproite plugs representing the uppermost parts of kimberlite plugs. The available chemical analyses of these rocks are graphically illustrated in Text fig. 10 in which however the minor substances cannot be shown—these minor constituents such as BaO, SrO, ZrO_2, TiO_2, P_2O_5 and F are comparatively abundant in these lamproites.

The volcanism giving rise to these lamproites was probably of very limited duration, at least as far as its surface manifestation was concerned and has produced very little effect on the intruded country rocks. These volcanic plugs have, however, been more resistant to erosion than the Permian sediments and at the present form the most marked features of the topography of this region.

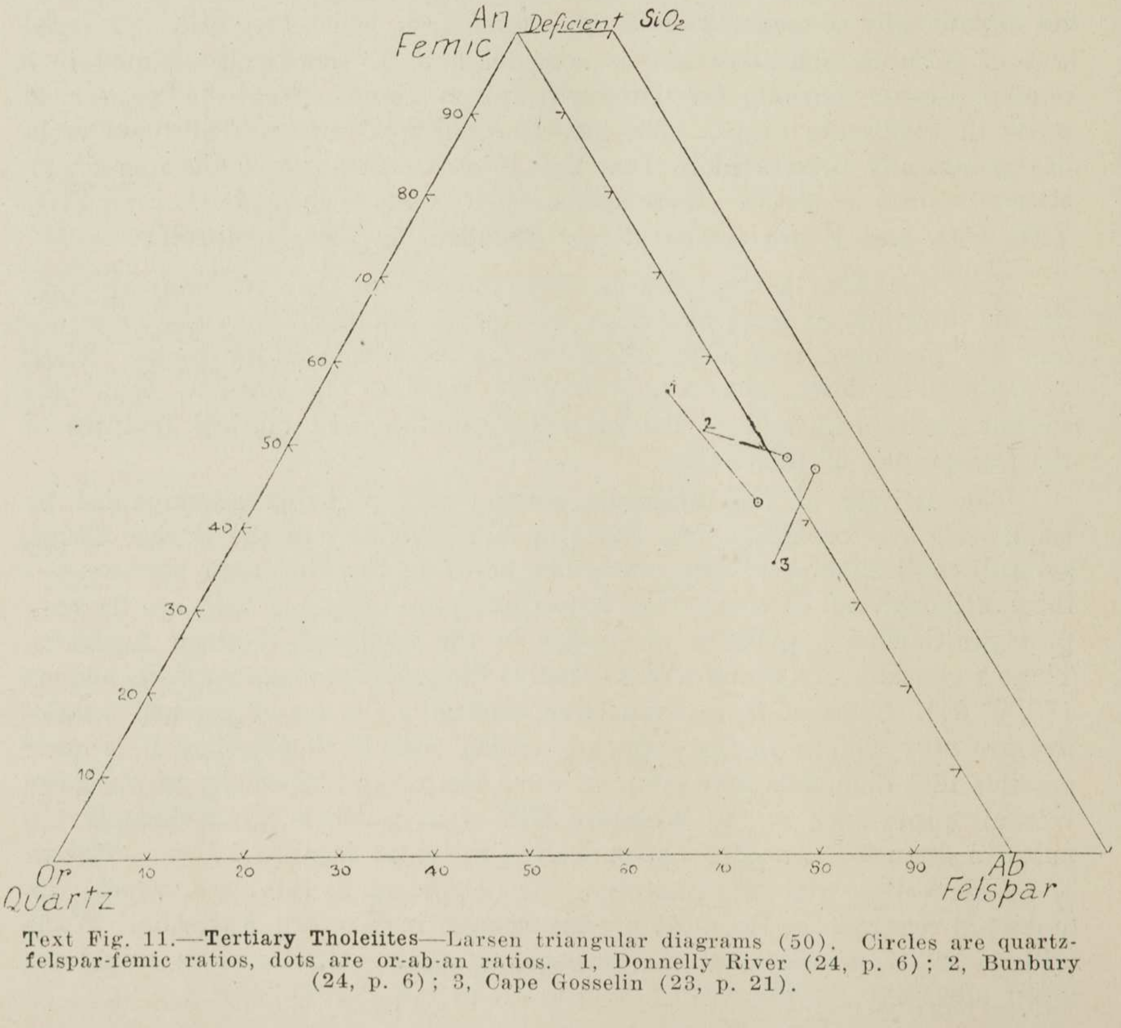
The activity of the lamproite magma was probably accompanied by small-scale ore-formation. At Narlarla in the vicinity of the Barker Gorge, several small silver-lead-zinc ore-bodies occur in the Devonian limestones—these, although not of commercial importance, are unique as they are the only post pre-Cambrian primary ore-bodies in the whole of Western Australia. These I consider are genetically related to the post-Permian lamproite magma (75, p. 64). Some of these lamproites, especially the coarse grained wolgidites are very similar to the diamond-bearing rock kimberlite and it is quite possible that diamonds may occur in these lamproites, especially in the large volcanic pipes such as the Wolgidee Hills vent which is approximately 1½ miles in diameter. Another economically important aspect of this volcanism is in connection with the prospects for petroleum in this area, which, up-to-date is regarded as the most promising area in Western Australia. Wade (98, p. 29) concludes that the presence of these volcanic vents would not affect adversely the chances of finding oil in this region,

B. THOLEIITES OF THE SOUTH-WEST.

These basaltic rocks are probably the youngest igneous rocks of Western Australia being considered to be of Sub-Recent age (19, p. 27). They occur

at various localities (24, p. 10) in the narrow trough-like area of younger rocks flanked at the east and west by Archaeozoic rocks, which extends from Geographe Bay to the south coast at Flinders Bay. The occurrence and petrology of these basalts has been dealt with by Edwards (23, 24) who finds that they are of tholeiitic character, of constant chemical and mineralogical composition but ranging from mega—to micro—porphyritic types. The available chemical analyses are illustrated in Text fig. 11. Insufficient evidence is available to indicate whether this period of igneous activity is represented by a single flow or by a series of separate flows, but borings at Bunbury (24, p. 11) indicate the presence of one flow only. Whether the flows noted in various places in the lower South West are fissure eruptions or flows from isolated vents is also unknown, but a study of the well marked curved joint systems in the Cape Gosselin outcrops (Text fig. 12) may yield information in this connection.

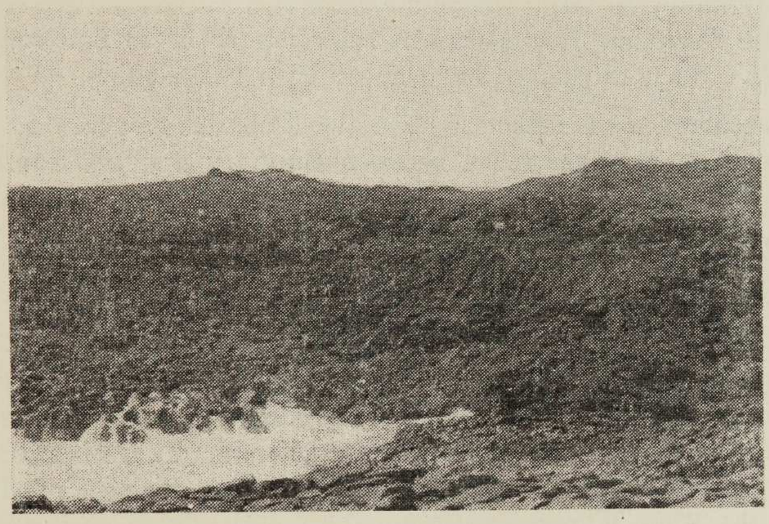
Edwards suggests (24, p. 8), following Gibb Maitland (57, p. 42) that the tholeiite magma was not confined to the south-west corner of the State but was more widespread, and he cites a number of localities where rocks which may be related to the Tertiary tholeiitic magma occur. On the occurrences listed (other than those of the norites, the age of which is unknown) the most likely, from their relations to the country rocks, to belong to this



Text Fig. 11.—**Tertiary Tholeiites**—Larsen triangular diagrams (50). Circles are quartz-felspar-femic ratios, dots are or-ab-an ratios. 1, Donnelly River (24, p. 6); 2, Bunbury (24, p. 6); 3, Cape Gosselin (23, p. 21).

Tertiary activity are the basaltic dolerites of the Meekatharra area. These basaltic dolerites, which are also represented in other goldfields areas, are the youngest igneous rocks in the Meekatharra area, being intrusive into the greenstones and auriferous ore bodies (11, p. 64). To the north of

Meekatharra the dolerites are reputed to intrude the Oakover limestones which were formerly considered to be possibly of Tertiary age (11, p. 64)



Text Fig. 12.—Curved columnar jointing in the Tertiary tholeiite flow at Cape Gosselin.
Photo—E. de C. Clarke

but which Finucane now regards as Permo-Carboniferous (34, p. 4). As there is a very great doubt regarding the age of the Oakover limestones (which may even be the dolomitic phase of the Upper Nullagine) the evidence is not sufficiently strong, in my opinion, to differentiate the basaltic dolerites of the Oakover occurrences from the quartz dolerite (tholeiite) dykes of late-Proterozoic or even Cambrian age.

Jutson and Simpson (48, p. 48) mention that "at the brick pit about three miles to the north-west of Albany, a decomposed basic dyke cuts through not only the granite, but also the overlying marine sediments (the Plantagenet beds of Miocene age) . . . and may possibly be related to the basalts of which those at Bunbury are the type." This "decomposed basic dyke" has never been closely examined and no material from it is preserved in the collection of the Western Australian Geological Survey. I am indebted to Mr. R. A. Fowler of Albany for several specimens of weathered rock which appeared to him to be the dyke rock described by Simpson and Jutson. Heavy mineral separations of this material (one specimen was white, the other reddish) showed that the heavy minerals were identical in both samples. The minerals noted in the heavy fractions were tourmaline, zircon, rutile, kyanite and magnetite, none of which show any signs of rounding. The same set of minerals with similar habit and shape was obtained by heavy mineral separations of a sample of "sediment of the Plantagenet Series" collected several years ago by Dr. Teichert, so there can be little doubt that the material collected for me by Mr. Fowler is from the Plantagenet beds. It is possible however that this material is not that described by Simpson and Jutson and further investigation is desirable to verify Jutson and Simpson's diagnosis since, other than the basalts outcropping between Bunbury and Cape Gosselin it is, if of igneous origin, the only example of undoubted Tertiary igneous activity in the southern half of the State. It may be noted here that the norite of Norseman, considered by Gibb Maitland (59, p. 82) and Edwards (24, p. 8) to belong to the Tertiary tholeiitic magma, is, according to Campbell (7, fig. 4 on p. 22) older than the Miocene fossil bed and therefore much older than the Albany "dyke" and the Bunbury basalt. It is most probable I think that

the basaltic dolerites of the Goldfields areas, rather than being of Tertiary age, are contemporaneous with the late-Proterozoic or Cambrian quartz dolerites and that the Tertiary tholeiites are confined to the trough extending from Bunbury to Cape Gosselin—otherwise we should expect somewhere amongst the Permian, Jurassic and Cretaceous rocks to find some traces of basic dykes. Such intrusives have never been recorded.

The occurrence of authentic Tertiary tholeiites appears to be confined to the trough of younger rocks between Bunbury and the South coast and this would indicate some tectonic significance for these outflows (60, p. 188), viz., that this trough, to which they are confined, is a rift valley.

VIII.—CONCLUSION.

This brings us to the end of our excursion through geological time in which we have glanced briefly at the evidences of igneous activity and related phenomena to be seen in Western Australia. There is no sign of present day igneous activity except possibly the hot springs of the Fitzroy Valley in the West Kimberley (3, pp. 11 & 29). These springs may be derived from deep artesian horizons, but I have noticed that water from comparatively shallow depths of one or two hundred feet is noticeably warm, indicating an abnormally high thermal gradient in this area. Is this due to some superficial phenomenon? Or is it evidence of igneous activity, either the waning activity of the lamproite magma, or evidence of an approaching period of volcanism in this area?

The subject of my address has, I feel, been an academic one, lacking the economically important nature of recent Presidential addresses to this Society, but in our geological studies we should not be hampered by being confined to economically important matters, but our efforts should be directed rather towards a better understanding of natural processes and the nature of the earth on which we live. If the publication of the matter which I have placed before you this evening provokes discussion, we cannot, I feel, do other than come to a better understanding of geological phenomena in Western Australia and in so doing equipping ourselves the better to undertake a very important responsibility in this world of quickly diminishing mineral reserves—the exploitation of our natural mineral resources.

IX.—ACKNOWLEDGMENTS.

It is a pleasure to record here my thanks to my colleagues, Professor E. de C. Clarke and Dr. Teichert of the Department of Geology of the University of Western Australia, and my friends Messrs. Forman, Ellis, Hobson and Matheson of the Geological Survey of Western Australia, for many helpful discussions concerning the igneous record in Western Australia. Professor Clarke has rendered me invaluable assistance in criticising the text of this paper and for such criticism I am very grateful. It gives me especial pleasure to record my indebtedness to Professor Clarke, to whom I owe my introduction to geology and who has always given freely of his advice and assistance in any research that I have attempted. I am indebted also to the Government Geologist (Mr. F. G. Forman) and the Government Mineralogist and Analyst (Mr. H. Bowley) for permission to quote from unpublished reports from their respective Departments.

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